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Evaluation of Emission Controls for Hazardous Waste Treatment, Storage, and Disposal Facilities

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The purpose of this report is to evaluate controls for volatile emissions arising from the treatment, storage, and disposal of hazardous wastes. For each principal type of hazardous waste management facility, sources of atmospheric emissions are described and controls representing different approaches, are examined and compared. The evaluation is based on actual data and on theoretical models where data are lacking or where the control technologies have been borrowed from other types of applications or are novel concepts. The information developed in preparing this report is intended to support the analysis of the regulation and control of these volatile emissions.

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TABLE OF CONTENTS

Page

I. SUMMARY AND CONCLUSIONS I-1

II. INTRODUCTION II-1

- A. Objective II-1
- B. Framework for the Analysis II-1
- C. Hazardous Waste Treatment, Storage and Disposal Disposal Facility--Definitions and Descriptions II-5
  - 1. Landfills II-5
  - 2. Land Treatment II-6
  - 3. Surface Impoundments II-6
  - 4. Storage and Treatment Tanks II-7
- D. Controls/Definitions and Description II-7
  - 1. Pretreatment Controls II-7
  - 2. Design and Operating Practices II-8
  - 3. In-Situ Controls II-8
  - 4. Post-Treatment Techniques II-8
- References II-10

III. CONTROLS FOR SURFACE IMPOUNDMENTS III-1

- A. Surface Impoundment Description III-1
  - 1. Definition III-1
  - 2. Types, Construction and Uses III-1
  - 3. Operation III-2
- B. Emission Sources and Models III-7
  - 1. General Description of Factors Affecting Emissions III-7
  - 2. Emission Models III-9
  - 3. Parameters That Control Emissions III-16
- C. Potential Controls III-17
  - 1. Introduction III-17
  - 2. Pretreatment III-18
  - 3. Design and Operating Practices III-18
  - 4. In-Situ Controls III-23
  - 5. Post-Treatment III-32

TABLE OF CONTENTS
(continued)

Page

D. Effectiveness of Surface Impoundment Controls III-36

1. Methodology III-36
2. Parameters III-40
3. Mass Transfer Coefficients and Emissions III-42
4. Emissions Reduction and Efficiencies III-42
5. Costs III-56
6. Cost-Effectiveness of Controls III-64

E. Summary III-69

F. References III-70

IV. CONTROLS FOR TANKS IV-1

A. Tank Description IV-1

1. Definition IV-1
2. Types, Construction and Uses IV-1
3. Operation IV-2

B. Emission Sources and Models IV-2

1. General Description of Factors Affecting Emissions IV-2
2. Emission Models IV-3
3. Parameters That Control Emissions IV-3

C. Potential Controls IV-3

1. Summary of Applicable Controls IV-3
2. Pretreatment IV-3
3. Design and Operating Practices IV-6
4. In-Situ Controls IV-6
5. Post-Treatment IV-8

D. Effectiveness of Surface Impoundment Controls IV-9

1. Methodology IV-9
2. Parameters IV-11
3. Emissions IV-11
4. Emissions Reduction and Efficiencies IV-11
5. Costs IV-15
6. Cost-Effectiveness of Controls IV-17

E. Summary IV-22

F. References IV-24

TABLE OF CONTENTS
(continued)

Page

V. LANDFILLS V-1

A. Landfill Description V-1
B. Emission Sources and Models V-2

1. General V-2
2. Emission Models V-3
3. Controlling Parameters V-7

C. Controls V-7

1. Introduction V-7
2. Pretreatment V-8
3. Design and Operating Practices V-8
4. In-Situ Controls V-16
5. Post-Treatment V-16

D. Effectiveness V-17

1. Introduction V-17
2. Effectiveness V-17
3. Costs V-25
4. Cost-Effectiveness V-28

E. Summary V-29

F. References V-30

VI. LAND TREATMENT FACILITIES VI-1

A. Description VI-1
B. Emission Sources and Models VI-2

1. General VI-2
2. Emission Models VI-2
3. Controlling Parameters VI-5

C. Controls VI-6

1. Introduction VI-6
2. Pretreatment VI-6
3. Operating Practices VI-6
4. In-Situ Controls VI-7
5. Post-Treatment VI-7

TABLE OF CONTENTS
(continued)

Page

D. Effectiveness VI-8

1. Introduction VI-8
2. Emissions Reduction and Effectiveness VI-8
3. Costs VI-12
4. Cost Effectiveness VI-12

E. References VI-13

LIST OF TABLES

TABLE NO. Page

I-1 RANGES OF EMISSION CONTROL EFFECTIVENESS I-3

II-1 EMISSIONS FROM HAZARDOUS WASTE TREATMENT, STORAGE AND DISPOSAL FACILITIES II-4

II-2 PRETREATMENT PROCESSES AND COSTS II-9

III-1 EVAPORATION SUPPRESSION BY SHADES III-26

III-2 SPHERE REQUIREMENT PER UNIT AREA AND VOLUME III-29

III-3 MASS TRANSFER COEFFICIENTS III-37

III-4 TYPICAL VALUES FOR WASTE PARAMETERS III-41

III-5 SURFACE IMPOUNDMENT SIZES III-43

III-6 SITE AND IMPOUNDMENT PARAMETER VALUES III-44

III-7 "TYPICAL" INDIVIDUAL k VALUES FOR SURFACE IMPOUNDMENTS WITHOUT CONTROLS III-45

III-8 MASS TRANSFER COEFFICIENTS (lb-mol/ft^2-hr) FOR SURFACE IMPOUNDMENTS WITHOUT CONTROLS III-46

III-9 EMISSIONS FROM SURFACE IMPOUNDMENTS WITHOUT CONTROLS (lb-mol/hr) III-47

III-10 CONTROLLABLE PARAMETERS TO REDUCE EMISSION RATES III-49

III-11 EMISSIONS REDUCTIONS AND EFFICIENCIES OF IN-SITU CONTROLS III-54

III-12 UNIT MATERIAL COSTS FOR SURFACE IMPOUNDMENT EMISSION REDUCTION IN-SITU TECHNOLOGIES (Dollars per Square Foot, Summer 1984 Dollars) III-57

III-13 ANNUAL COSTS FOR SURFACE IMPOUNDMENT CONTROLS, $/YR (Summer 1984 Dollars) III-59

III-14 RELATIVE INSTALLATION AND OPERATION/MAINTENANCE COSTS III-60

III-15 CAPITAL COSTS FOR COLLECTION SYSTEM FOR POST-TREATMENT (Summer 1984 Dollars) III-63

III-16 COMPARATIVE COST-EFFECTIVENESS FOR IN-SITU EMISSIONS CONTROLS III-65

LIST OF TABLES
(continued)

TABLE NO.		Page
IV-1	RELATIONSHIPS DESCRIBING EMISSION LOSSES IN TANKS	IV-4
IV-2	PARAMETERS FOR TANK EMISSION RELATIONSHIPS	IV-5
IV-3	PARAMETER VALUES FOR TANKS	IV-12
IV-4	EMISSIONS REDUCTIONS AND EFFICIENCIES OF CONTROLS IN TANKS	IV-13
IV-5	TOTAL COSTS AND ANNUALIZED COSTS FOR CONTROLS (Summer 1984 Dollars)	IV-16
IV-6	COMPARATIVE COST-EFFECTIVENESS FOR TANK IN-SITU CONTROLS	IV-18
V-1	RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTION	V-10
V-2	RELATIVE DIFFUSIVITY AS A FUNCTION OF SOIL POROSITY	V-12
V-3	UNIT EMISSIONS THROUGH 12-INCH SOIL COVERS FOR SOILS OF DIFFERENT DRY POROSITY	V-18
V-4	UNIT EMISSIONS THROUGH MEMBRANE CAPS	V-21
V-5	ANNUAL EMISSIONS	V-24
V-6	ESTIMATED UNIT COSTS FOR SOME COVER LAYERS	V-26
V-7	POST-TREATMENT COLLECTION SYSTEM COST ESTIMATES	V-27
VI-1	ANNUAL LOSSES FROM 1 ACRE OF LAND TREATMENT	VI-10

LIST OF FIGURES

FIGURE NO.		Page
II-1	GENERALIZED FLOW OF VOLATILE EMISSIONS	II-1
III-1	CROSS-SECTION-SURFACE IMPOUNDMENT	III-3
III-2	SURFACE IMPOUNDMENT CLOSURE KEY STEPS	III-5
III-3	EFFECT OF TEMPERATURE ON EMISSIONS (50th Percentile Size Impoundment)	III-51
III-4	EFFECT OF WIND SPEED ON EMISSIONS (50th Percentile Size Impoundment)	III-52
III-5	EFFECT OF GEOMETRY CHANGE ON EMISSIONS (50th Percentile Size Impoundment)	III-53
III-6	COST-EFFECTIVENESS OF IN-SITU SURFACE IMPOUNDMENT CONTROLS	III-66
III-7	COST-EFFECTIVENESS OF SURFACE IMPOUNDMENT CONTROLS VERSUS THROUGHPUT (50th Percentile Size)	III-67
III-8	COST-EFFECTIVENESS OF SURFACE IMPOUNDMENT CONTROLS VERSUS REDUCTION	III-68
IV-1	EFFICIENCIES OF IN-SITU CONTROLS FOR TANKS	IV-14
IV-2	COMPARATIVE COST-EFFECTIVENESS OF IN-SITU CONTROLS FOR TANKS	IV-19
IV-3	COST-EFFECTIVENESS OF CONTROLS ON TANKS VERSUS THROUGHPUT	IV-20
IV-4	COST-EFFECTIVENESS OF CONTROLS ON TANKS VERSUS REDUCTION	IV-21
V-1	RELATIVE DIFFUSIVITY IN SOIL COVERS	V-11
V-2	EXAMPLE STANDARD COMPACTION CURVES FOR VARIOUS SOIL TYPES	V-13
V-3	TYPICAL LAYERED COVER SYSTEMS	V-15
V-4	UNIT EMISSIONS THROUGH 12" SOIL COVER OVER A LANDFILL	V-19
VI-1	PERCENT OF VOLATILES LOST TO ATMOSPHERE	VI-9
VI-2	REDUCTION EFFICIENCY FOR SUBSURFACE INJECTION RELATIVE TO SURFACE INJECTION	VI-11

I. SUMMARY AND CONCLUSIONS

Volatile emissions from hazardous waste treatment, storage and disposal facilities (TSDFs) represent a major source of organic contaminants entering the atmosphere. The emissions contain a wide range of organic constituents, which contribute to both oxidant generation and also to exposure to potentially hazardous air pollutants. Previous studies prepared for EPA estimate that volatile emissions from surface impoundments, storage and treatment tanks, landfills and land- treatment facilities range from 1.6 to about 5 million metric tons per year. The lower estimate represents about one-third of emissions of some 54 organic chemicals from all sources including industry and transportation. These 54 chemicals are the most volatile and toxic compounds appearing in wastes regulated under RCRA.

Surface impoundments are the largest source of emissions, providing about half of the total. Treatment and storage tanks make up about one-third of the total, with treatment tanks contributing about 50 times as much as storage tanks. Landfills produce about 12% and land treatment adds the remainder, about 3%.

TSDFs, particularly offsite commercial operations, generally treat complex mixtures of wastes. The wastes deposited in landfills historically have included a wide range of solvents, PCBs, industrial wastes, sludges and still bottoms, etc. The resultant emissions integrate volatile species from all of the wastes present in the landfill. Impoundments at large industrial facilities often serve the entire complex, receiving wastes of many different types. Treatment tanks and land-treatment facilities, on the other hand, are more often dedicated to a narrower mix of wastes.

The principal focus of the current Federal and state TSDF regulatory program has been on the prevention of groundwater contamination during and after the active life of disposal facilities, the prevention of exposure from atmospheric emissions of the products of incineration, and the prevention of accidental exposures in general. There has been little emphasis on prevention of exposure from direct emissions of volatile compounds in the wastes. This study examines the availability of controls for four principal types of TSDFs and evaluates the cost and effectiveness of each.

Four different classes of controls are examined. These are:

- pretreatment
- design and operating practices
- in-situ controls
- post-treatment techniques

Pretreatment includes technical controls and administrative measures (bans) that, in essence, prevent volatile wastes from reaching the TSDF in the first place. These types of controls obviously reduce the quantity of organics that will ultimately be emitted from TSDFs, and also reduce the rate of loss since the processes that control emission are proportional to waste concentration. The volatile materials that have been removed must be subsequently treated or disposed, however.

Design and operating practices and in-situ techniques can reduce the rate of loss from the facility. These controls include approaches such as floating covers for impoundments and tanks, improved temporary and permanent cover design and moisture control for landfills, and subsurface injection at landfills. The use of wind screens to lower wind speed over impoundments in order to reduce mass transfer from the surface also falls into this class.

Finally, post-treatment can be used to catch emissions that escape even if other approaches are used. This type of system involves some sort of collection system coupled with a process to remove or destroy the volatile components. Air-inflated structures have been installed at several locations including an aerated surface impoundment (about 0.4 acre). This system includes a carbon adsorption unit designed to remove the volatiles and recycle them to the aerated impoundment where biological degradation ultimately will destroy the wastes. Thermal incinerators could be used instead of adsorption system to destroy the volatile compounds.

The effectiveness of the four types of controls ranges from moderately effective to very high, potentially 99% or above (See Table I-1). The values in Table I-1 have been generated from first principles or have been taken from experience at related types of facilities. The validity at real hazardous waste TSDFs is unknown. The values shown may be overly optimistic or, in some cases, conservative. Substantial experimental work is needed, as noted further below, to verify the estimates developed and presented herein.

Pretreatment and post-treatment can achieve removal (and in some cases destruction) efficiencies of 90%. Wastes removed but not destroyed must be handled in additional steps to prevent emissions from occurring. Recycling as feedstocks, reclaimed solvents, etc. represents essentially complete control. The figures for pretreatment and post-treatment are quite reliable as the treatment technologies have been demonstrated on process streams comparable to hazardous wastes. Inflated covers as large as six acres have been shown to be practical. Systems of this size would fit most existing facilities. Future facilities could be designed with operating units compatible with the largest cover then available.

Pretreatment works best on wastes of reasonably well-defined and constant properties. The most likely opportunities are at on-site industrial plants and for solvent recovery. On the other hand, pretreatment may not fit well with the complex wastes going off-site

TABLE I-1

RANGES OF EMISSION CONTROL EFFECTIVENESS

Pretreatment	> 90% (removal)
Post-Treatment	> 90% (removal)
Operating Practices and In-Situ Controls (rate reduction)	
Surface Impoundments	
Rafts/Spheres	80 - 90%
Wind Screens	10 - 15%
Tanks (relative to open tanks)	
Rafts/Spheres	80%
Fixed Roof	90%
Floating Roof (external)	90%
Floating Roof (internal)	> 95%
Landfills	
Improved Cover Practices	> 90%
Land Treatment	
Subsurface Injection	20 - 90%

Source: Arthur D. Little, Inc.

to commercial TSDFs. The volume and composition of the wastes may be so variable that pretreatment would not be technically feasible, or, if feasible, would cost more than the figures used in this and other studies.

In-situ controls and improved design and operating practices are promising. The values shown in the table are, as noted above, based on theoretical principles as there are little or no data extant on emission controls at these types of facilities. Several of the in-situ technologies (shades, wind screens, for example) have been used in similar, but distinctly different settings. The validity of these techniques at hazardous waste TSDFs should be established. Using improved soils and controlling moisture in temporary and permanent covers at landfills can, according to the estimates made below, reduce emissions essentially to zero. In practice, however, there will be limitations to achieving such efficiencies. There are no data available to determine how closely this limit can be approached.

Pretreatment appears to be a cost effective control relative to the other types of controls particularly if only small quantities of volatiles are present in the wastes. Pretreatment costs according to another EPA study are about $2-4,000 per megagram (Mg)($1-2 per pound) of volatiles, (Spivey et al., 1984). Post-treatment costs are considerably more. The treatment portion alone ranges from about $11,000 per megagram removed ($5 per pound) upwards. The lower figures are for catalytic incineration or regenerative adsorption. If the recovered wastes have market or fuel value the costs will drop substantially. Thermal incineration without heat recovery and non-regenerative carbon adsorption cost upwards of $33,000 per megagram ($15 per pound) of volatiles removed. The collection system will add to this figure, but for large facilities the added cost will be incremental to the treatment cost on a pound removed basis.

The cost effectiveness of in-situ approaches can potentially be very high for those operating practices that require little additional labor or equipment. Moisture control at landfills or subsurface injection at land treatment facilities are good examples. The added cost of these practices is very small relative to the cost of conventional practices, so that the control potentially achievable per dollar would be high. On the other hand, the absolute effectiveness that is achievable in practice may not attain acceptable levels. In these cases, pre- or post-treatment may be used as an adjunct.

At the conclusion of the analysis there remain many unanswered questions generally as a result of the lack of good data characterizing emissions or the performance of controls at hazardous waste TSDFs. It is recommended that field and laboratory programs be carried out to obtain such data. In particular, data describing the effectiveness of cover practices at landfills; injection, cultivation, and application density practices at land-treatment facilities; and rafts, floating spheres and covers at impoundments and tanks should be developed.

The estimates developed in this report assume no losses occur through degradative processes in the TSDF or equivalently that volatilization and reaction are uncoupled. This assumption is not valid in reality at these facilities. Reducing emission losses may change the overall degradative efficiency per pound of volatile waste entering the system. The direction of such change is not clear at this time. Studies examining this coupling should be carried out both in the laboratory and field and also through theoretical modeling.

Reference

Spivey, J.J., et al., Preliminary Assessment of Hazardous Waste Pretreatment as an Air Pollution Control Technique. Research Triangle Institute for the USEPA (February 1984).

II. INTRODUCTION

A. Objective

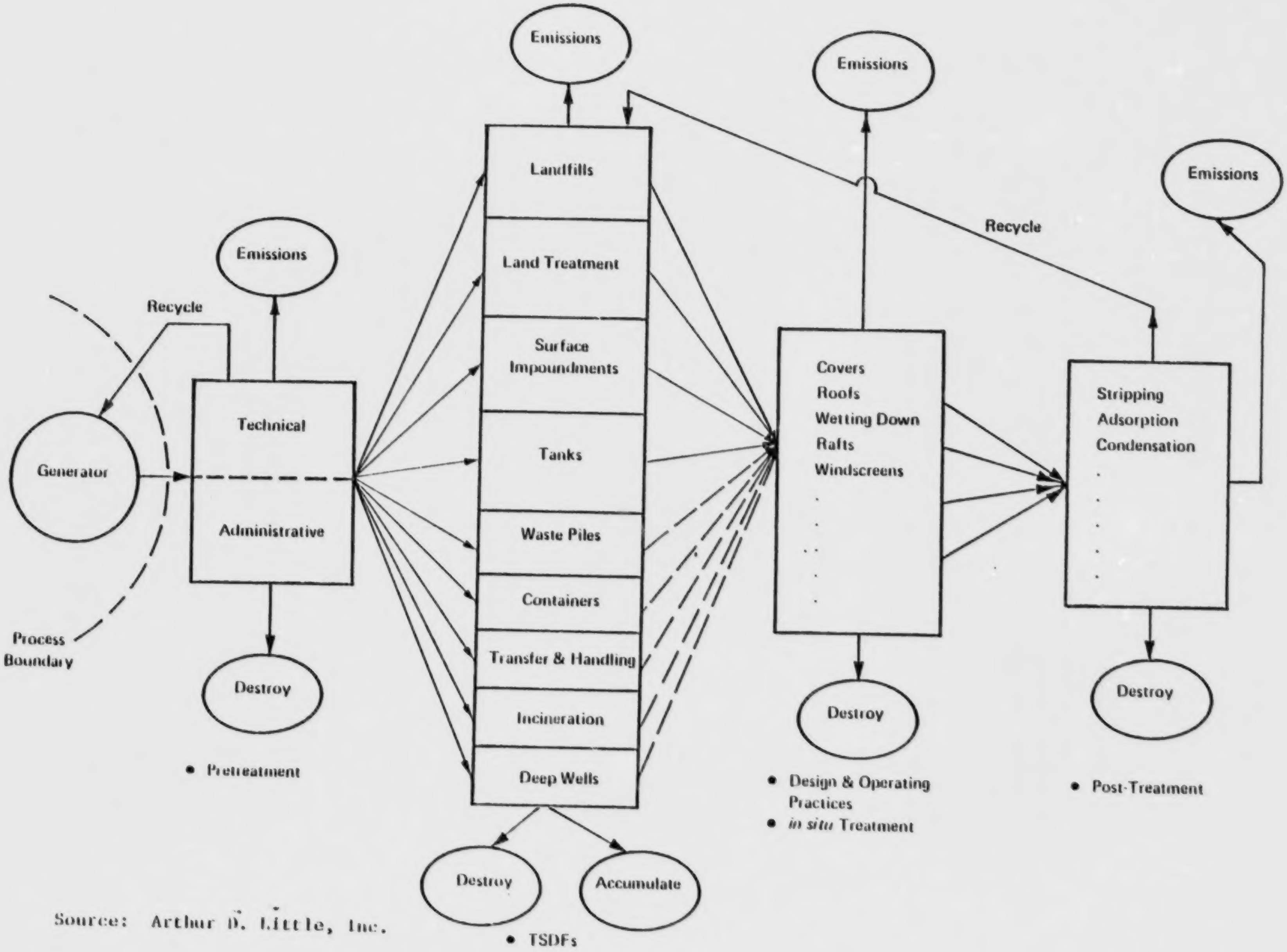
The purpose of this study is to evaluate controls for volatile emissions arising from the treatment, storage, and disposal of hazardous wastes. For each principal type of hazardous waste management facility, sources of atmospheric emissions are described and controls representing different approaches, are examined and compared. The evaluation is based on actual data and on theoretical models where data are lacking or where the control technologies have been borrowed from other types of applications or are novel concepts. The information developed in the study is intended to support the analysis of the regulation and control of these volatile emissions.

B. Framework for the Analysis

Emissions from hazardous waste treatment storage and disposal facilities (TSDFs) have been estimated to be in excess of 1.5 million metric tons per year (Breton et al., 1983). The worse case estimate provided in the above reference is in excess of 5 million metric tons per year. To put this value in perspective, volatile organic compound emissions from industry, transportation, and other sources have been estimated to be 10.7, 7.7, and 3.9 million metric tons per year, respectively (Breton, et al., 1983). In parts of the country where compliance with oxidant standards has not been attained or is difficult, control of the emissions from TSDFs may represent a significant opportunity for improvement in ambient air quality.

Federal and state air quality regulations for both industry and transportation sources contain a family of provisions designed to reduce or eliminate volatile organic compound emissions to the atmosphere. Very stringent regulations have been adopted in regions with severe oxidant problems. The regulations that govern the treatment, disposal, and storage of hazardous wastes, however, do not explicitly provide for control of volatile emissions. The main thrusts in the regulations promulgated to date have been to protect surface water and groundwater.

The overall system for the treatment, storage, and disposal of volatile hazardous wastes is depicted in Figure II-1. This figure schematically illustrates potential sources of atmospheric emissions and opportunities to impose controls to reduce those emissions. Starting at the left-hand side, wastes are created by industrial, commercial, and other generators. The generators, by employing waste reduction and recycle practices within their process boundaries (that is, within their plant or facility) can reduce the quantities of wastes produced in the first place. Although such techniques can provide a substantial potential impact on volatile emissions reduction, this report looks only at the processes that take place



Source: Arthur D. Little, Inc.

FIGURE II-1 GENERALIZED FLOW OF VOLATILE EMISSIONS

once the wastes have left the process boundary and move either offsite or to the hazardous waste disposal portions of the generator's facility.

A variety of hazardous waste treatment, storage, and disposal techniques can be used. These are shown in the second column of the figure. The principal methods include landfills, land treatment, surface impoundments, waste piles, storage and treatment tanks, incineration, and deep well injection. The potential for emissions from incineration and deep well injection is considered to be very small compared to the other processes, and are not considered further in this study. Waste piles, containers, and transfer and handling operations are also omitted. GCA has estimated the relative emissions from the various types of TSDFs as shown in Table II-1 (Breton et al., 1983). The emissions calculation is based on some 54 chemicals listed specifically in the hazardous waste regulations. The total emissions of all volatile organics is estimated to be higher as is implied by the worst case estimate given above. Surface impoundments contribute over half the total emissions. Treatment tanks rank next, contributing about one-third of the estimated emissions. Land treatment adds the smallest quantity of the facilities included. The original reference to these data contains a number of caveats concerning the accuracy in the use of the numbers. The data are presented here to demonstrate the importance of this problem. For a more comprehensive examination of the sources of emissions, the original reference should be examined.

Control of emissions from the TSDFs can be accomplished through several means; pretreatment techniques, design and operating practices, in-situ techniques, and post-treatment techniques. Pretreatment controls are those administrative or technical procedures applied to wastes prior to being sent to a TSDF, which will reduce their emissions in those treatment, disposal, and storage facilities. Design and operating practices are techniques within control of the designer and operator that can reduce emissions without interfering with other, generally primary, objectives. In-situ treatments are defined as technologic means and are operating practices employed within, and as a part of the TSDF, that will reduce emissions from those facilities. Finally, post-treatment techniques are defined as procedures that can be used to remove volatiles from the streams that emerge after the imposition of in-situ treatment techniques to the atmosphere.

To evaluate the effectiveness of emission control methods, it is important to have a sense for the flow of volatile materials in the hazardous waste management process. Some controls may appear to be very effective, but only transfer the emissions from one part of the process to another. For example, an administrative ban of certain organic compounds from landfills will obviously reduce the potential of emissions of the prohibited compounds from the landfill to zero, but the wastes must then be treated or disposed of by some other procedure. If this other procedure is a non-emitting technique such

TABLE II-1

EMISSIONS FROM HAZARDOUS WASTE TREATMENT, STORAGE, AND DISPOSAL FACILITIES

Facility Type	Estimated Annual Emissions[*] (10^3 Metric Tons/Yr)
Treatment Tanks	530
Non-Aerated Surface Impoundment - Storage	420
Non-Aerated Surface Impoundment - Treatment	310
Landfill	190
Non-Aerated Surface Impoundment - Disposal	66
Aerated Surface Impoundment	66
Land Applications	43
Storage Tanks	10
Total	1,635

---

[*] For 54 selected chemicals.

Source: Breton et al.. 1983.

as incineration, then such an administrative control can be very effective. If, on the other hand, the procedure is an alternative such as extended storage or disposal in a surface impoundment, then a ban would not be so effective when the potential emissions from the entire chain of events is accounted for.

As volatile materials move through the hazardous waste management process, they must be destroyed, accumulated, emitted or recycled to a prior step at each stage. This report examines in detail the effectiveness of design and operating practices and in-situ treatment techniques, and also the use of post-treatment methods to reduce subsequent emissions. A similar detailed analysis of pretreatment methods is not included. The effectiveness of pretreatment controls has been the subject of a study being carried out at Research Triangle Institute for the EPA (Spivey et al., 1984). Results of that study have been incorporated directly as a basis to show comparisons.

The studies referenced above approached the analysis from the perspective of the types of wastes, particularly the work of Spivey, et al., (1984). The approach herein is different, examining controls from the point of view of type of facility. The choice of control method is largely dictated by facility and environmental setting, not by waste properties. In certain cases, however, the effectiveness depends on waste properties. These cases are spelled out in the text.

Effectiveness is measured primarily by degree of reduction of the rate of emissions, not by reduction in total emissions over long periods of time. Many controls serve only to retard this rate of emission; for example, improved covers at a landfill. Others remove the volatile materials entirely, for example, pretreatment or post treatment, although the wastes removed may require subsequent treatment or disposal. Retarding the rate of loss by volatilization keeps the materials in the facility for longer periods. If other loss mechanisms occur, such as biological decay, then reducing the emission rate may change the absolute quantity emitted over time. It is not possible to predict the direction of the change, based on present data and theory. Mechanisms leading to either an increase or decrease can be invoked.

C. Hazardous Waste Treatment, Storage and Disposal Facility--Definitions and Descriptions

1. Landfills

Landfills are disposal facilities in which hazardous wastes are placed in containers or in bulk form, covered over with soils and left indefinitely. The present regulations require that free liquids must be mixed with a suitable bulking agent. Some state regulations now ban the disposal of certain types of organic liquids entirely. Other states are contemplating similar bans. Pre-RCRA and early RCRA regulations permitted the landfilling of free liquids. Emissions from landfill operations arise during the daily operation during which period wastes are placed within the landfill. Emissions can arise from liquids spilled on the ground or from solids, sludges, and bulk liquids which are exposed to the atmosphere. Once the material has been placed within the landfill and covered, emissions can occur from compounds vaporizing within the wastes, that diffuse toward the surface and escape to the atmosphere. A cover is generally applied at the close of each day, and is a permanent cap is installed on top when operations within a single cell have come to a close.

Landfills have three operational stages. The first is the active life during which waste is disposed within the landfill cell on a daily basis. The second is the closure period during which a completed cell is capped and taken out of operation and capped. Finally, the post-closure period is an extended period of monitoring and inspection that follows the closure of an individual cell and ultimately of the entire landfill. A single cell is generally designed to operate for a period of one to two years, whereas the active life of the entire landfill may be in the range of 10 to 20 years, and in the case of a few very large landfills, many decades.

2. Land Treatment

Land treatment is a means of waste management in which wastes are deposited on and worked into soil so that natural processes can degrade and demobilize the hazardous constituents within the waste. Biological activity detoxifies some of the organic constituents. Inorganic constituents may be immobilized by adsorption or other processes that bind the elements to soil particles.

Emissions from land treatment facilities arise, first, by volatilization from the wastes that have been spread on the soil prior to being incorporated within the top layers. A second source is wastes which have been mixed into the soil, but which continue to release volatile materials which diffuse upward through the soil and reach the surface.

3. Surface Impoundments

Surface impoundments are large basins created by excavation or by constructing dikes. Wastes generally containing large quantities of water are placed in the impoundments for either treatment or storage. Storage impoundments are generally nonaerated and are often used for the disposal of sludgy materials. Nonaerated impoundments are also used to evaporate water from aqueous wastes, leaving behind the residual solids and sludges. Atmospheric emissions are produced by the volatilization of compounds within the impoundment or at the surface followed by their diffusion into the atmosphere. In some cases, biological activity takes place under anaerobic conditions below the surface of the impoundment. When this occurs, the impoundments are often denoted as facultative. The biological activity can produce gases which bubble up through the impoundment. Under these circumstances the gas bubbles can also carry volatile materials to the surface.

Surface impoundments can also be aerated. Aeration is provided to enhance biological activity within the body of the impoundment, degrading the organic materials contained. The principal mechanism for emissions remains that of diffusion at the surface. The turbulence created by the aeration changes the rate of diffusion at the surface relative to the quiescent regions or to a nonaerated impoundment cover.

4. Storage and Treatment Tanks

Treatment and storage tanks come in a wide variety of sizes and shapes. Wastes are stored and treated both in open tanks and in tanks with covers and roofs. In uncovered tanks the mechanism of loss to the atmosphere is similar to that in surface impoundments. Diffusion from the liquid surface to the atmosphere is the only means of escape. The details of diffusion at the surface, like surface impoundments, depend on whether the tank is quiescent or is being mixed by a impeller. The mechanism for fixed roof tanks is primarily the same mechanism. Volatile materials diffuse from the surface into the head space above the liquid, and then in general, are released to the atmosphere through some sort of vent. Vents are necessary in most storage tanks to control changes in pressure due to temperature variations and volumetric changes due to filling and emptying. On Pressure tanks are designed to withstand the changes of pressure without vents. No losses to the atmosphere would take place under normal operations from this type of tanks.

Floating roof tanks, commonly used to store bulk petroleum products, may be used for the storage of large volumes of organic solvents. In these tanks a roof floats on the surface of the liquid and is stabilized by means of a seal along the circumference. Losses to the atmosphere occur by leakage at the seal and by adherence of the stored fluids to the tank walls as the roof drops during emptying operations.

D. Controls/Definitions and Description

1. Pretreatment Controls

Pretreatment controls include administration and technical measures. Administrative controls, such as bans or restrictions on the disposal of volatile materials in landfills, surface impoundments, or land treatment facilities have been instituted by several states and will be implemented in the future by the Federal government. Such controls have the effect of completely eliminating the potential of emissions from the facility in question. In evaluating the overall effectiveness of these controls, however, the ultimate means of treatment or disposal used must be considered.

Technical controls include methods which separate the volatile materials from the wastes and either recycle them back to the generator or other potential users, or destroy the potentially volatile materials through subsequent treatment. Separation techniques include:

- Distillation
- Stripping
- Carbon Adsorption
- Solvent Extraction

Each of these methods can be used to remove a fraction of the volatile materials from the waste stream. The choice depends on the particular composition of the waste. Once separated, the volatile fraction can be reused or destroyed by incineration with air oxidation and other more exotic methods. Some emissions may occur during the separation and treatment process, but they will be less than the emissions that would have occurred if the wastes had been deposited on the land or in treatment tanks in their original form.

Table II-2 shows a list of typical pretreatment processes and unit costs.

2. Design and Operating Practices

This class of emission controls covers a great variety of approaches. Many are specific to one kind of treatment, storage, or disposal process. For example, emissions can be controlled by modifying the operating cycle at a land treatment site or by designing an impoundment to minimize surface area. Careful choice of cover materials and moisture control can, in theory, reduce emissions at a landfill by several orders of magnitude.

3. In-Situ Controls

These are controls that can be used to provide efficiency beyond that which good practices can achieve. They include covers for most of the facilities, roofs, wind screens, and others. The opportunities to use such devices at hazardous waste management facilities are somewhat limited. In-situ controls may interfere with the basic functioning of the TSDF. The distinction between in-situ controls and operating practices is arbitrary. Both could be included in a single class for the purposes of this analysis.

4. Post-Treatment Techniques

Several techniques are available to isolate or destroy the volatile components provided that they are in the form of a well-defined stream. Volatiles may be recovered, for example, from the vent of a storage tank by refrigeration/condensation or adsorption on activated charcoal. The recovered volatile material could be returned to storage or to the treatment facility.

TABLE II-2

PRETREATMENT PROCESSES AND COSTS

Waste type	Applicable Pretreatment process	Example cost $/metric ton of organic material removed or recovered
Organic liquids	Distillation	251
Aqueous, up to 20% organic	Steam stripping	151
	Solvent extraction	55
Aqueous, less than 2% organic	Steam stripping	151
	Carbon adsorption	1,600
	Resin adsorption	310
	Air stripping with carbon adsorption	1,400
	Ozonation/radiolysis	1,800
	Wet oxidation	1,390
	Biological treatment	68
Sludge with organics	Air stripping with carbon adsorption	1,400
	Ozonation/radiolysis	1,800
	Wet oxidation	1,390
	Chemical oxidation	91,000
	Evaporation with carbon adsorption	140
Some sludge in organic or aqueous stream	Physical separation ($8/metric ton of waste treated for sludge removal)	

Source: Spivey et al, 1984.

Alternatively, post-treatment techniques that destroy the volatiles can be used. These consist of techniques such as flares, ozonation, thermal incineration, and the like.

References

Breton, M. et al., 1983. Assessment of Air Emissions from Hazardous Waste Treatment, Storage, and Disposal Facilities (TSDF's) - Preliminary National Emissions Estimates -- Draft Final Report - GCA Corporation for the USEPA. GCA Report No. GCA-TR-83-70-G (August 1983).

Spivey, J.J. et al., 1984. Preliminary Assessment of Hazardous Waste Pretreatment as an Air Pollution Control Technique, Draft Final Report -- Research Triangle Institute for the USEPA (February 1984).

III. CONTROLS FOR SURFACE IMPOUNDMENTS

A. Surface Impoundment Description

1. Definition

Surface impoundment means a facility or part of a facility which is a natural topographic depression, man-made excavation, or diked area formed primarily of earthen materials (although it may be lined with man-made materials), which is designed to hold an accumulation of liquid wastes or wastes containing free liquids, and which is not an injection well. Examples of surface impoundments are holding, storage, settling, and aeration pits, ponds, and lagoons (Federal Register, May 19, 1980). Exceptions to the above definition include concrete-lined basins, which are, by definition, considered tanks.

2. Types, Construction and Uses

As defined above, surface impoundments may be natural or man-made depressions. Acreages range from less than an acre to hundreds of acres and depths vary from 2 feet to as much as 30 feet below the land surface (EPA, 1982). Impoundments are generally built above the naturally occurring water table. Future impoundments handling hazardous wastes will have to be above the water table to comply with federal and state regulations. Some may be constructed on the land surface using dikes or revetments. Natural topographical features such as valleys or depressions may be diked on one or more sides to form the containment area. Dikes may also be required for impoundments in areas of high water tables or to take advantage of impermeable surface soils (EPA, 1982). The three major categories of impoundments are: (1) totally excavated; (2) filled; and (3) combination. Excavated impoundments are those dug from a surface so that the major portion of the capacity is below the grade of the surrounding land surface. Filled impoundments are built above grade such that the majority of the capacity is above the immediate surroundings. Combination impoundments result when material is both excavated and filled. Most impoundments are combination excavation-fill impoundments. Excavated material is used to build side walls, berms, basal areas, and for other miscellaneous construction needs (EPA, 1980).

Surface impoundments are used for a large variety of purposes. These uses can be generalized into temporary holding, treatment, or disposal of wastes. Surface impoundments are used for: treatment by biodegradation, stabilization, equilization, oxidation, evaporation, settling, and for sludges, tailings, and cooling water, among many varied uses. A settling pond is a very common use for a surface impoundment as a means to separate suspended solids from liquids by gravity. Chemical additives may be added to accelerate solids coagulation and precipitation. Settling can be a pre- or post-treatment operation. Surface impoundments may be periodically dredged to restore them to their original capacity. Settling is essentially a quiescent operation but emissions to the air can occur. Temporary storage of liquid wastes can be from a few days to quite an extended period. These wastes may be stored before appropriate treatment or stored as a post-treatment operation before disposal. As mentioned above, treatment operations may be performed in a surface impoundment. These treatment processes may involve aeration by mechanical aerators or may be non-aerated. Biodegradation may be aerobic, anaerobic, or facultative.

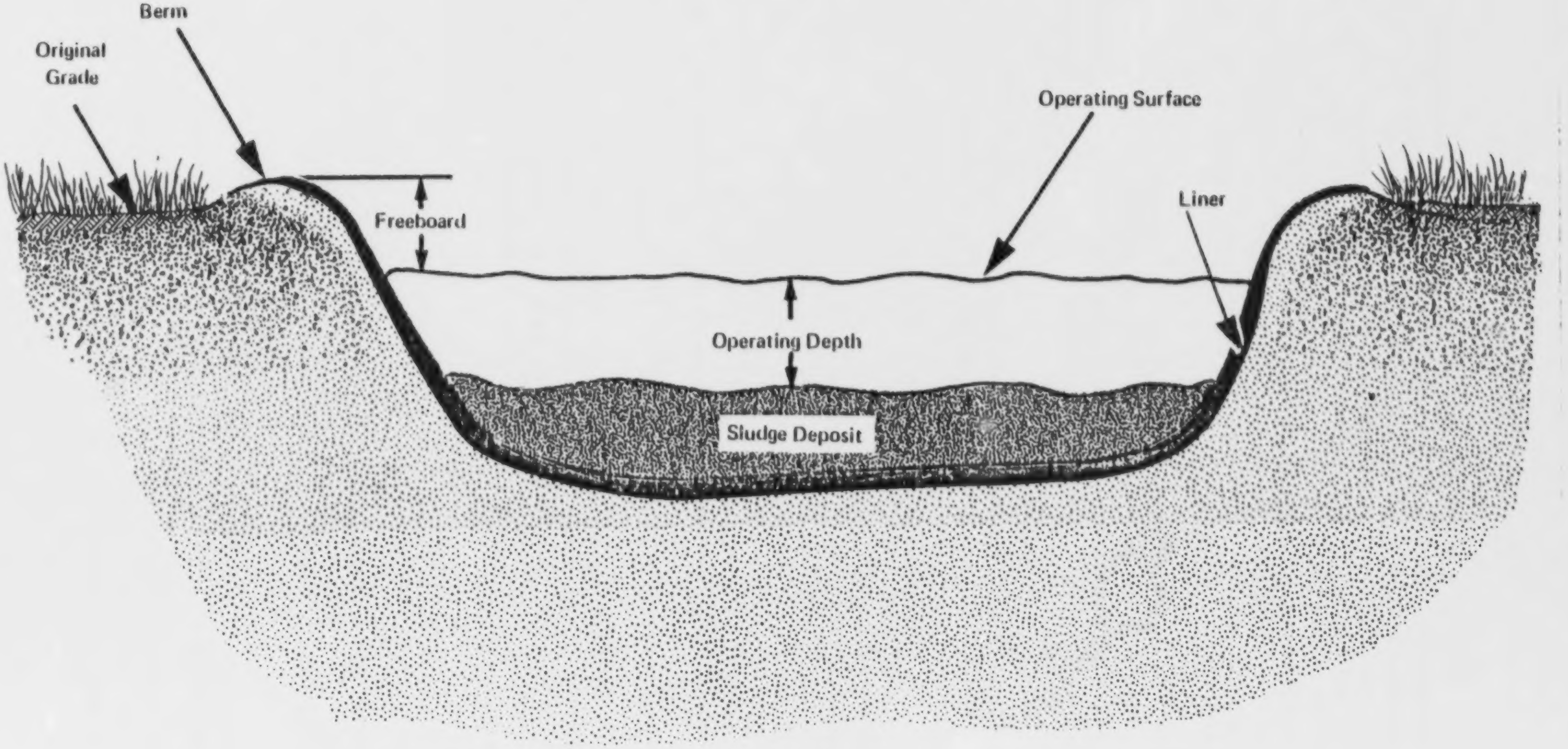
3. Operation

There are three phases to the life of a surface impoundment after it is constructed. These three phases are: active, closure, and post-closure. The operation of a surface impoundment varies during each phase of its life-time and will be described separately.

3.1 Active

The active phase of a surface impoundment encompasses times prior to closure when the facility is accepting waste or is dormant for long periods. Because of the varied uses and large range of sizes of surface impoundments, the operation of a surface impoundment during its active phase will vary greatly from impoundment to impoundment. The surface impoundment may be receiving mainly sludge or mainly liquid hazardous waste, or mixtures of both. Each surface impoundment has a specified capacity for containing wastes depending on the design and on the volume already contained in the impoundment as shown in Figure III-1. The operating surface area, that is, the area exposed, varies with the depth of waste in the impoundment. The operating depth is defined as the distance from the surface to the lowest point of the bottom of the impoundment, and the freeboard is the depth from the top of the berm to the liquid surface. The surface impoundment may be designed with weirs, spillways, auto level controls or other means of preventing overtopping. The impoundment may be lined or unlined, and may contain a leakage detection system.

Impoundments may be operated individually or interconnected so that the flow moves from one impoundment to another in series or parallel. Depending on the use of an impoundment, it may be operated under steady-state or unsteady-state conditions, and it may be mechanically mixed to encourage aeration or not mixed at all. A steady-state operation is one in which the rate of inflow is equal to the rate of outflow and losses through evaporation or removal (in the case of solids).



Source: Arthur D. Little, Inc., 1984

FIGURE III-1 CROSS-SECTION-SURFACE IMPOUNDMENT

Wastes are taken into the surface impoundment at a certain frequency. The average rate of flow and temperature of the influent varies greatly from impoundment to impoundment. The influent pipe may be submerged and wastes entering the impoundment from inside the bulk of the waste or the waste may be added onto the surface of the bulk waste. Wastes could enter the impoundment with or without pretreatment. The length of time wastes are kept in the impoundment before removal is called the retention time. If the surface impoundment is used for disposal, the total disposal capacity is important.

In certain uses, the solids in surface impoundments are removed at intervals so that the design capacity of the impoundment is restored. Such uses include settling ponds, precipitation lagoons, sludge holding, and tailing ponds. The rate of sludge or sediment accumulation is dependent on the inflow rate and the composition of the influent wastes. Dredging is the usual method for removing solids. The frequency of dredging will depend on sludge or sediment accumulation rate and the capacity of the surface impoundment.

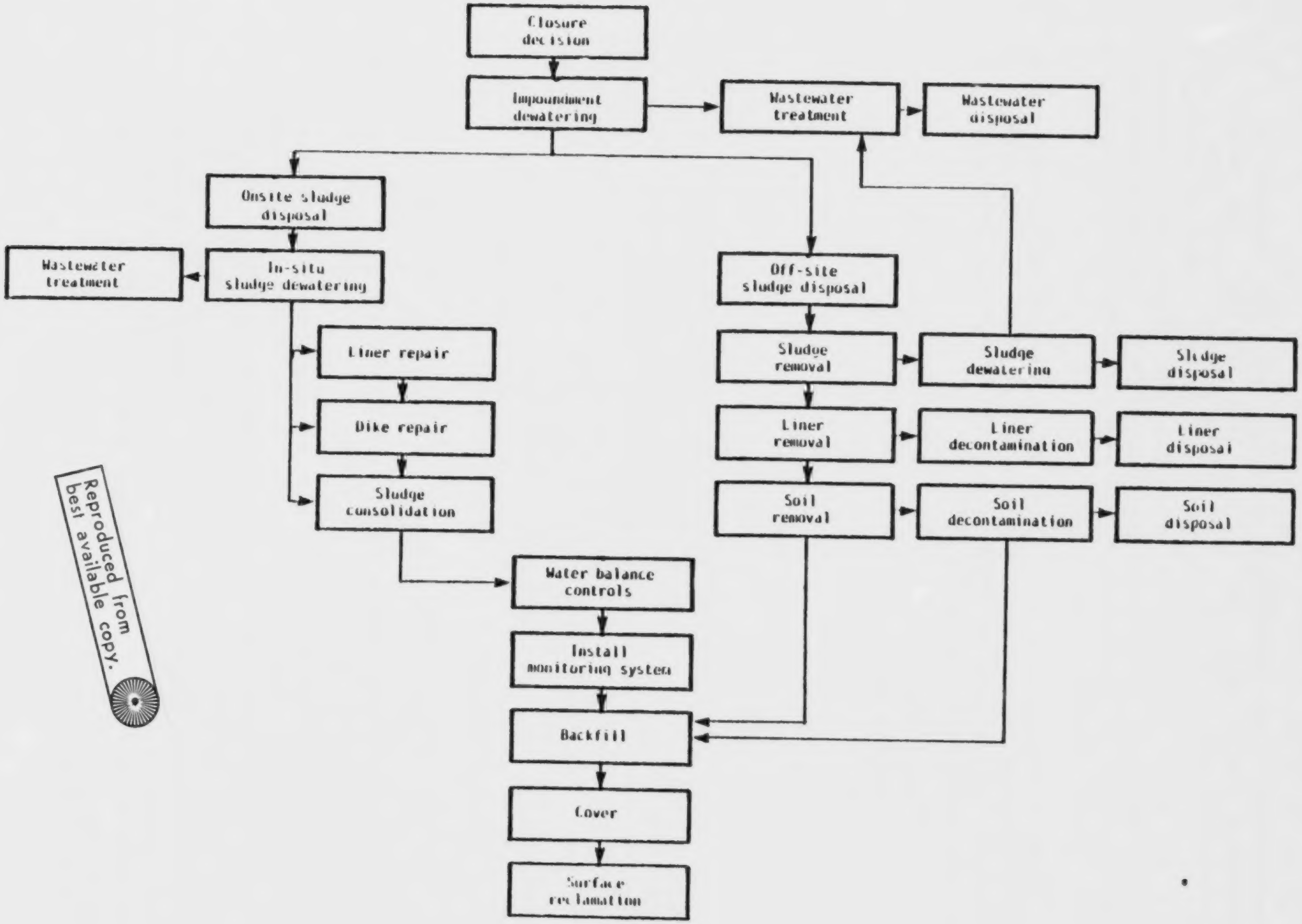
Liquids are removed from surface impoundments periodically or continuously. The frequency of discharge of liquids and the method of discharge are dependent on the use of the impoundment. Some impoundments lose their liquids by evaporation or infiltration into the soil underneath. In the past, seepage of fluids were permitted for the purpose of percolation or infiltration. All new impoundments containing hazarous wastes must be lined to prevent any seepage. Discharge through evaporation is dependent on the physical and chemical properties of the wastes and the meterology and climatology of the site. Direct discharge may originate at the surface of an impoundment or within the bulk of the waste.

Surface impoundments may be totally drained and/or most of solids removed after some years of storage to clean out the impoundment, to restore the impoundment to full capacity, to make repairs if necessary, or to close the facility permanently as the next section describes.

3.2 Closure

Surface impoundments are generally constructed to be temporary containment structures. The service life of impoundments may vary and when the surface impoundment reaches the end of its active life, the impoundment undergoes a closure phase.

Closure of hazardous waste surface impoundments is discussed in detail in EPA (1982). There are two basic ways to close a surface impoundment: wastes and waste residuals are left in the impoundment after closure, and wastes and waste residuals are removed from the impoundment site. The key steps in surface impoundment closure are shown in Figure III-2. If hazardous wastes are to remain in the impoundment, procedures must be implemented to minimize the release of



Reproduced from best available copy.

Figure III-2 Surface Impoundment Closure Key Steps

Source: U.S. Environmental Protection Agency, September 1982 contaminants into groundwater, soils, and the atmosphere. The remaining wastes must not contain free liquids. The wastes are consolidated and stabilized, and the impoundment closed with a cover like a landfill. Some impoundments may be best closed by removal of all the waste and residuals, including the liners and contaminated soils. These are transported and disposed in another acceptable site. The site may be reclaimed by filling, leveling, and revegetation. Site closure procedures are varied.

The first step in the closure of an impoundment is dewatering, involving the removal and disposal of standing liquid before the residual solids can be removed or the sediments dewatered. The various methods of dewatering are:

- Decanting
- Pumping and settling
- Solar drying
- Infiltration
- Process reuse
- Chemical neutralization
- Absorbents

Several techniques may be used to remove the dewatered sediments as a slurry (wet) or as a dry solid (dry). Wet methods are to: resuspend as an air or water jet and then pump the slurry; or to excavate if sediments are hardened and non-flowing. Excavation techniques are high-pressure water or air jets, high-speed rotary cutter, or clamshell bucket. Dry methods require that the sediment be dried by evaporation and then removed by vacuum transport or excavation. The liner and contaminated soil may be removed from the impoundment as well, using normal excavation methods. The site is filled in and restored as far as possible by revegetation.

If the residual wastes are to be left in place, the wastes must have the consistency of nonflowable solids according to EPA guidelines. Further dewatering of the drained sediments may be needed either by passive or active dewatering. During the dewatering, the flowable sediment is consolidated to a nonflowable solid. Volume reduction may be further achieved by further consolidation physically, biologically, or chemically depending on the sediment characteristics. Biological oxidation can reduce the mass of solids by conversion to liquid and gaseous end products. Similarly, chemical consolidation can convert a portion of the waste solids to a dissolved or gaseous product which is removed with leachate or released to the atmosphere. The wastes can be further stabilized through solidification or encapsulation to produce a solid, chemically nonreactive material. After consolidation, the site can be closed as a landfill with a cover and vegetation.

3.3 Post-Closure

Once the surface impoundment is closed, it essentially is a closed landfill and has to be maintained as such (see section on landfills).

B. Emission Sources and Models

1. General Description of Factors Affecting Emissions

Emissions to the atmosphere may occur during all phases of the operation of a surface impoundment. Organic gases and fugitive dust may be emitted during the active life of a surface impoundment, during closure, and after closure.

Active

Vaporization of organics at the surface from floating immiscible layers or from the bulk aqueous wastes is the main process for emission losses during the active life of a surface impoundment. Some losses can also occur through vaporization of organics from the exposed walls of the impoundment if organics have migrated into the soil or liners. These losses are not considered in this analysis.

The rate of waste volatilization in impoundments is dependent on the physical and chemical properties of the waste and the surrounding environment. The natural factors affecting the rate of volatilization include wind, temperature, humidity, and solar radiation. The rate of emission into still air is slower than evaporation into the wind. Vapor pressures increase with increasing temperature and surface turbulence, either by wind or by mechanical agitation, increases the rate of volatilization. The characteristics of the waste affecting its rate of volatilization include its Henry's law constant and solubility.

Gases may be generated by reactions within the impoundment. Biological activity may decompose organics to produce methane, hydrogen sulfide, carbon dioxide, or other gases. These biological reactions may be aerobic or anaerobic depending on the conditions within the impoundment. These reactions may be encouraged by the operators of an impoundment through the addition of microorganisms to the impoundment and the aeration of the impoundment using mechanical aerators or agitators. Emissions would be increased in such cases due to the generation of more gases from decomposition and from increased turbulence on the impoundment surface. Chemical reactions may also increase emissions if gases are produced. Mixing used to increase the rate of reaction will increase emissions.

Another source of emissions during the active life of an impoundment are particulates generated by wind and human activity. Wind erosion of wastes depend on waste type, moisture content, wind velocity, and surface geometry. If a dry layer of waste forms on the surface of an impoundment, wind or human activity on top of the impoundment may induce erosion of this layer.

During discharging, pumping, dredging, or removing of impoundment sediments, additional emissions may be expected from several sources:

- liquid surfaces can be renewed and vaporization is increased,
- dried surfaces or crusts can be removed, venting entrained gases and creating a liquid surface,
- pressures can be changed and residue components mixed, affecting gas venting and production,
- turbulence of impoundment surface increasing vaporization,
- generation of spray from operations,
- drying of dredged material,
- movement of equipment may cause fugitive emissions of contaminated soil.

Closure

The closure process includes operations that will generate emissions. During dewatering, volatilization is expected to increase due to pumping and decanting. If solar drying is used, emissions will be greatly increased if volatile organics are present. During excavation, fugitive dust will be emitted. Exposed waste surfaces are susceptible to wind erosion and to the mechanical movement processes of the excavation equipment. Weather conditions affect the generation of fugitive dust emissions. During excavation, the waste will become drier due to volatilization of liquid from increased handling of the waste material.

If the impoundment is to be closed by leaving the wastes in the impoundment, further dewatering will increase gaseous emissions due to volatilization and wind erosion of dry waste will be increased. Consolidation is also expected to produce gaseous emissions.

Post-Closure

If the impoundment is improperly closed, various organic compounds may still volatilize under the cover. Gases may be generated from biological and chemical reactions. Anaerobic biological activity may increase. These emissions may be released through the cover, or through cracks in the cover if not properly vented. More details of emissions after closure are given in the discussion on landfills.

2. Emission Models

The basic relationship describing the flow of compounds in and out of a surface impoundment is the material balance around the impoundment. In the most general case, this relationship is:

$$\frac{dw}{dt} = \dot{W}_{in} - \dot{W}_{out} - Q_{vol} - Q_{seep} \pm Q_{react}$$

where w = quantity of a waste compound in the impoundment at time t (lb)

$\dot{W}_{in}$ = quantity of compound entering in influent (lb/hr)

$\dot{W}_{out}$ = quantity leaving in discharge (lb/hr)

Q_{vol} = quantity volatilizing (lb/hr)

Q_{seep} = quantity seeping through liner (lb/hr)

Q_{react} = quantity lost or gained through reaction (lb/hr)

Each of the separate terms is a function of concentration. The solution is expressed as the function of concentration over time. Evaluation of the effectiveness of evaporative controls in the general case would involve solving the equation for two cases, one with and one without controls, for a unit mass of volatile compound entering the system. Comparison of the volatile emissions integrated over time would provide the desired measure of control efficiency.

In the general case, the equation is complex and difficult to solve. Non-aerated impoundments are poorly mixed so that concentration varies throughout the system. In this case, the equation shown is not quite proper; a partial differential equation should be used. Aerated ponds behave more like mixed systems. Reaction loss due to biological degradation is non-linear. Evaporative loss in the general case, depends not only on the efficiency of control, but on the relative rates of the other loss mechanisms.

For evaluative purposes, it is convenient to simplify the analysis by neglecting seepage and reactive (for example, biodegradation) losses and assuming steady-state. This set of assumptions reduces the governing equation to the simple form below. Mass is expressed in lb-mols. Under this set of assumptions, the effectiveness of a control is the reduction in instantaneous rate of emissions relative to the no control case. But, given the no other losses and steady-state assumption, all of the incoming materials would eventually volatilize.

The basic relationship governing emissions from the surface of an impoundment is the instantaneous mass flow equation.

$$Q' = K_{oa} A (X_L - X^*)$$

where Q' = mass flow $(\frac{\text{lb - mol}}{\text{hr}})$

A = exposed area (ft^2)

K_{oa} = overall mass transfer coefficient (lb-mol/ft^2-hr)

X_L = mol fraction of diffusing component in liquid

X^* = mol fraction in equilibrium with gas phase concentration

The same functionality may be expressed in a different format using other variables in place of mol fraction.

Several additional relationships can be introduced to reflect dependence on specific properties of the diffusing component and of the overall system. One useful form of relationship between the equilibrium mol fraction and the concentration in the gas phase is:

$$y = Kx^*$$

where y = mol fraction of component in gas phase

K = equilibrium constant, dimensionless

For dilute aqueous solutions, the equilibrium constant in this format is approximately related to the conventional Henry's Law constant as:

$$K \cong \frac{H\rho_w}{P_T \, MW_w}$$

where H = Henry's Law constant $(\frac{\text{atm - ft}^3}{\text{lb-mol}})$

ρ_w = density of liquid water (lb/ft^3)

MW_w = molecular weight of water

P_T = total pressure (atm)

At one atmosphere,

$K = 3.47H$

The overall mass transfer coefficient, K_{oa}, can be expressed, using the conventional two-film theory of mass transfer, as:

$$\frac{1}{K_{oa}} = \frac{1}{k_L} + \frac{1}{k_G K}$$

where k_L = liquid film mass transfer coefficient ($\frac{lb\text{-}mol}{ft^2\text{-}hr}$)

k_G = gas-film mass transfer coefficient ($\frac{lb\text{-}mol}{ft^2\text{-}hr}$)

Expressions for the individual liquid and gas film coefficients have been derived from theoretical and experimental bases (See GCA, 1983). The appropriate choice depends on the similarity of the situation being modeled to the conditions in the laboratory or theory from which the formula was derived. For surface impoundments, two regimes are important, aerated and non-aerated.

Gas film, non-aerated

In the non-aerated case, the liquid surface is relatively quiescent, although waves may be created by wind action, increasing the effective area for transport. The following relationship selected for k_G (see GCA, 1983) was developed by MacKay and Matsuga (1973).

$k_G' = 0.0432\, u^{.78}\, D_p^{-.11}\, (N_{sc})^{-.67}$

k_G' = gas film coefficient (ft/hr)

u = wind speed (ft/hr)

D_p = effective pool diameter (ft)

N_{sc} = Schmidt number = $\frac{\mu_g}{\rho_g D_{i,air}}$

where: μ_g = gas absolute viscosity $\left(\frac{lb}{ft\text{-}sec}\right)$

$D_{i,air}$ = diffusivity of ith component in air (ft^2/hr)

ρ_g = gas density (lb/ft^3)

To convert k_G to units consistent with the basic definitions above,

$$k_G = k_G' \frac{P_T}{RT}$$

where R = gas constant (ft^3-atm/°R-lb-mol)

T = temperature (°R)

At one atmosphere and 77°F (25°C), the resultant equation is:

$$k_G = 1.1 \times 10^{-4} \; u^{.78} \; D_p^{-.11} \; (N_{sc})^{-.67}$$

Liquid film, non aerated

The liquid phase coefficient, k_L, is taken from Owens et al (1964) as modified by Hwang (1982).

$$k_L = 3.12 \; (1.024)^{\theta-20} \; u_o^{.67} \; H_o^{-.85} \left[\frac{D_{i,\,H_2O}}{D_{O_2,\,H_2O}}\right]$$

k_L = liquid phase coefficient (lb-mol/ft^2-hr)

Θ = ambient temperature (°C)

u_o = wind speed at surface (ft/sec)

H_o = effective depth of impoundment (ft)

The wind speed at the surface may be approximated as a factor of the normal wind speed; the factor 0.035 is cited in the above references.

The original form of Owens relationship was applicable to flowing streams and showed a dependency on stream velocity and depth. The form used in this study, as modified by Hwang, accounts for upper layer movement induced by wind over the surface. The correlation developed by Cohen et al., (1978) is perhaps, more applicable but was not used. The choices of Hwang's form of the Owens relationship is consistent with several other studies related to volatile emissions from hazardous waste TSDFs (Breton et al., 1983; Spivey et al., 1984).

Gas-film, aerated

For aerated portions of impoundments, the coefficients are quite different, reflecting the highly turbulent nature of mass transfer in this kind of system. The gas-film coefficient follows the work of Reinhardt (1977) as reported by Hwang (1982).

$$k_G = .00039 \frac{(\rho_g D_{i,\,air})}{D_T \, MW_i} (N_{re})^{1.42} (N_{fr})^{-.21} (N_p)^{.4} (N_{sc})^{0.5}$$

where k_G = gas film coefficient $\left(\frac{\text{lb-mol}}{\text{hr-ft}^2}\right)$

ρ_g = gas density (lb/ft^3)

$D_{i,air}$ = diffusion coefficient of ith component in air (ft^2/hr)

D_T = diameter of aerator turbine or impeller (ft)

MW_i = molecular weight of ith component

N_{re} = gas Reynolds number = $\frac{\rho_g D_T^2 \omega}{\mu_g}$

where ω = impeller rotational speed (radian/sec)

μ_g = gas abolute viscosity $\left(\frac{lb}{ft\text{-}sec}\right)$

N_{fr} = Froude Number = $\frac{\omega^2 D_t}{g}$

where g = gravitation constant (32.2 ft/sec^2)

N_p = power number = $\frac{P_r g}{\rho_L \omega^3 D_T^5}$

where P_r = power to impeller (ft-lb/sec)

ρ_L = liquid density (lb/ft^3)

N_{sc} = Schmidt Number = $\frac{\mu_g}{\rho_g D_{i,air}}$.

The representation of the aerated portions of a surface impoundment used herein is highly idealized. In more sophisticated models, the aerated region is considered to have two portions, a central, highly turbulent region within the boundary of the aerator, and a second region outside the inner zone where flow moves radially outward (Lunney et al., 1984). The more simplified version used is sufficient to illustrate the general dependency of volatile emissions on a variety of potential controlling variables.

Liquid film, aerated

The liquid phase coefficient for the aerated portions is taken from Thibodeaux (1978).

$$k_L = \frac{J\, P_r\, n\, (1.024)^{\theta-20}\, \alpha\, (10^6)}{165.04\, a_v\, V} \left[\frac{D_{i},\, H_2O}{D_{O_2},\, H_2O}\right]^{0.5}$$

where:

k_L = liquid phase coefficient $\left[\frac{lb\text{-}mol}{ft\ \text{-}hr}\right]$

J = oxygen transfer rating of aerator $\frac{lb\text{-}O_2}{hr\text{-}hp} \cong 3$

η = efficiency of power conversion ($\eta \cong .65 - .90$)

α = oxygen transfer correction factor ($\alpha \cong .8 - .85$)

a_v = surface area to volume ratio (ft^{-1})

V = volume of impoundment within the effect of the aeration (ft^3)

The aerated portions of an impoundment generally cover only a fraction of the total surface area. Average mass-transfer coefficients are developed by using area-weighted coefficients for the aerated and non-aerated portions.

Referring back to the two film theory equation combining the contributions of both gas and liquid film coefficients, it can be seen that:

if $k_L >> K\,k_G$

then $K_{oa} \cong K\,k_G$

and

if $k_L << K\,k_G$

then $K_{oa} \cong k_L$

That is, if mass transfer through the gas film is very much slower than the liquid film (the first case above), the gas film controls the process. If the situation is reversed, (the second case above), the mass transfer is liquid-film controlled. For non-aerated surfaces, under normal conditions, the mass transfer is liquid-phase controlled, that is, diffusion through the liquid surface is slower than through the air at the surface. Under high wind speed conditions where the surface may become roiled, the situation can shift more toward a balance.

Floating Immiscible Organic Layer

In this case, only the gas film, non-aerated coefficient is important.

$$K_{oa} = K k_G$$

where K = partial pressure of the pollutant in the air layer next to the organic layer.

$$K = P_{vp}/P_T$$

where P_{vp} = vapor pressure of pollutant, atm.

P_T = total pressure = 1 atm.

At atmosphere pressure measured in atmospheres,

$$K_{oa} = P_{vp} k_G$$

3. Parameters That Control Emissions

The derivations above were developed in detail to provide a basis for describing mechanisms that lead to atmospheric emissions and to indicate the factors that can be controlled to reduce these emissions. The basic mass flow equation shows that the rate of emission depends on the overall coefficient, the exposed area, and the concentration or mole fraction in the liquid. The concentration in the gas phase in uncovered impoundments is effectively zero, as fresh air continually sweeps over the system.

Pretreatment controls function by reducing the mole fraction in the liquid. The effectiveness is linearly proportional to the degree of removal. If 50% of the potentially volatile materials are removed, then the rate of emission, and also ultimately the total quantity of wastes entering the atmosphere will be halved.

Another broad category of controls function by reducing the area exposed. The effectiveness of such controls is also by and large expressed as a linear relationship. If the area is reduced by 80%, then the emission rate would be reduced in proportion. The total quantity of materials volatilized, assuming no other loss mechanism, would not be changed over the long run. The time to volatilize a unit quantity of waste would increase inversely with the resultant emission rate. In the above example, the time during which emission would occur would be five (5) times that which would occur with no control.

A third approach to control of emissions is through the mass transfer coefficient. For the non-aerated portions the controlling mechanism is described by the Owens Equation above. The controllable parameters that determine the value of the mass transfer coefficient are the wind speed at the surface (u_o) and the effective depth (H_o). Barriers and fences, as described in the sections below, can be placed to reduce the wind speed. The relationship is not linear, and it is difficult to relate the reduction in wind speed to barrier design. The dependence on depth is inverse, that is, deeper impoundments have, in theory, lower mass transfer coefficients. The choice of depth is often dictated by overall capacity and land availability constraints, but given a choice, this relationship indicates that deeper impoundments would result in reduced rates of volatilization. This set of relationships is only approximate as real behavior departs from the idealization implicit in the Owens equation. But the general dependence on wind speed and depth is expected to be found in practice.

The above discussion of the two-film theory and of the controlling parameters is based on the assumption that the volatile materials are present as a dilute aqueous solution. It is also possible to have a layer of lighter-than-water, immiscible organic compounds floating on the surface. In this case, the controlling mechanism will be diffusion in the gas phase, not the liquid phase. The MacKay and Matsuga type of relationship should generally illustrate the dependence of mass transfer coefficient on the operating parameters for this case. Reducing the wind speed, as in the general aqueous case, should inhibit the rate of volatilization.

For gas-phase controlled situations, the rate of mass transfer depends on the Henry's Law constant as well as the individual mass transfer coefficient. This parameter is quite strongly temperature dependent, increasing with increasing temperature. Controls which reduce the impoundment surface temperature would, thus, inhibit the rate of volatilization, when this mechanism controls.

C. Potential Controls

1. Introduction

Controls to reduce atmospheric emissions from surface impoundments can be applied at different stages in the operation of an impoundment. If no volatile wastes were allowed into the surface impoundment in the first place, then volatile organics could not be emitted unless degradation forms volatile by-products from semi-volatiles. The surface impoundment can be designed and operated at each phase with the primary objective of reducing air emissions. Such practices may (and generally would) interfere with the basic functions of the impoundment. In situ technologies can be added on to a surface impoundment to control those parameters that influence emission rates; e.g., wind speed, mass transfer coefficient, effective surface area, etc. Finally, emissions can be collected and treated before being released into the atmosphere. For each control within these general approaches, the mode of action, the expected effectiveness and related costs are discussed.

2. Pretreatment

Pretreatment basically removes the volatile components of a waste before it is put into a surface impoundment. Pretreating a waste may consist of air-stripping and carbon adsorption or condensation of the volatiles. The stripped waste may then be put into an impoundment with decreased potential of volatile organic volatilization. For a general discussion of pretreatment, see Spivey et al, 1984.

The effectiveness of this control is dependent on the efficiency of the pretreatment process. The concern here is that air emissions are not being transferred from the impoundment to the pretreatment system. If the volatiles that are generated in the pretreatment process are not properly recovered or disposed of, the final result may be that overall, air emissions would not have been reduced.

The costs associated with this control are (see Spivey et al, 1984):

- pretreatment system costs.
- cost of recovery of volatiles (e.g., carbon adsorption, condensation, etc.).
- cost for treatment of recovered volatiles (if not reused).
- disposal cost for all wastes associated with pretreatment, recovery (e.g., spent carbon), and treatment of recovered volatiles.

3. Design and Operating Practices

At the present time the issue of air emissions is generally not a primary consideration in the design and operation of surface impoundments. Most of the concern is with the control of leaching from surface impoundments into groundwater and with other functions of the impoundment, such as evaporation or settling. It is conceivable that impoundments could be designed and operated differently if concerns about air emissions are incorporated into the initial decision-making process. Potential design considerations to control air emissions are: surface area minimization, freeboard depth, and inflow/outflow drainage pipe locations. Operations during the active life involving temperature of influent, dredging frequency, draining frequency, cleaning frequency, handling of sediments and sludge from dredging and types of wastes accepted at a facility could be designed to minimize emissions. Closure practices to prevent fugitive dust emissions during excavation and excessive volatilization during dewatering and consolidation may be instituted. After closure, the surface impoundment is essentially a landfill. Post-closure practices may be found in the section on landfills.

This discussion will be divided into: design, operating practices-active, and operating practices-closure.

3.1 Design

3.1.1. Surface Area Minimization

As seen from the model on air emissions from surface impoundments, the rate of emissions is directly proportional to the operating surface area. Theoretically, for a certain capacity surface impoundment, minimization of surface area with respect to depth would decrease air emissions. But, this approach would not be applicable to impoundments where other constraints determine surface area. For example, it would not be practical to use this approach for an evaporation lagoon since the purpose of the impoundment would be thwarted.

Costs probably will be higher than with conventional designs because of potential engineering difficulties. To reduce surface area, the side slopes of the impoundment could be increased as much as possible subject to erosion considerations, the ability to hold a liner, and the ease of construction (trafficability). Due to the greater care that is needed, costs are expected to be higher.

Other important considerations require that the efficiency of treatment in the impoundment should not be significantly decreased. Aeration and mechanical mixing would be reduced in efficiency because of increased depth.

3.1.2 Freeboard Depth

Increase in freeboard depth will decrease wind and wave action on the surface of the impoundment. This will decrease:

- volatilization,
- turbulence on the impoundment surface,
- spray formation, and
- erosion of dust and the dried surface of the impoundment.

This control is expected to be effective in many settings. Field experiments with in-situ windbreakers have indicated that evaporation from reservoirs have been reduced significantly (see section on in-situ controls). The most important parameter in determining the effectiveness of the deeper freeboard is the ratio of freeboard depth to diameter of the impoundment (distance from edge to edge). The larger this ratio, the more effective this control will be.

To increase freeboard, the height of the berm could be increased or the impoundment could be filled to an average smaller depth. The cost factors are:

- cost of material for berm
- labor costs
- costs for more frequent draining of impoundment

The draft RCRA Guidance Document (July, 1982) suggested at least 60 cm (2 feet) of freeboard to prevent overtopping. A way to increase freeboard is to minimize run-on into the impoundment by incorporating a run-on control system. For large lagoons, other in-situ controls to break the wind may be more effective since a very large freeboard may be necessary to achieve enough wind-breaking.

3.1.3 Inflow/Outflow Drainage Pipe Locations

Again, the idea of this control approach is to minimize disturbance of the surface of the impoundment. Inflow pipes discharging above the liquid surface create turbulence on the surface and may also cause spray formation. Any dry crust on the surface will be destroyed. This dry crust is helpful in reducing emissions by creating a barrier or a cover on the surface. Inflow pipes should be designed to discharge below the surface of an impoundment and as far as possible, into the bulk of the liquid in the impoundment. Similarly, outflow systems should pump out liquid from the bulk of the surface impoundment.

More power is required to pump a discharge into the bulk of a liquid. This translates into higher energy costs.

3.2 Operating Practices - Active

3.2.1 Temperature of Influent

The vapor pressure of a liquid increases with temperature. Also, when two liquids of different temperatures are mixed, convective currents are induced which cause mixing. This disturbance of the system will increase volatilization from the surface. To reduce air emissions, the influent should be discharged at as close a temperature to the bulk of the liquid as possible.

It is unknown how effective this control would be in reducing air emissions in actuality. Evaporation ponds would not be an appropriate impoundment for application since the efficiency of evaporation would be reduced. Another consideration is that treatment efficiencies will be reduced if temperatures are reduced. Most reaction rates are higher at higher temperatures. Oxidation ponds, aerobic and anaerobic lagoons are impoundments which may be affected by reduction of temperatures.

Costs are expected from cooling influent before discharging into an impoundment. A heat exchanger may be needed.

3.2.2 Dredging, Draining, and Cleaning Frequency

The more frequently a surface impoundment is disturbed, the more emissions will be released. One way to decrease emissions is to minimize dredging, draining, and cleaning frequency. The reduction in emissions will be proportional to reduction in frequency of dredging, draining, and cleaning. Costs would be reduced because both labor and equipment costs would be decreased. There is a trade-off in cost and efficiency of an impoundment. For cost reasons, most impoundments are already drained, dredged, and cleaned as infrequently as possible without overly impacting the performance of the impoundment.

3.2.3 Handling of Sediments and Sludge

After treatment and removal from an impoundment, sediments and sludges may be dewatered before disposal in another facility. Some methods for dewatering and disposal cause more air emissions than others. Solar drying will cause more air emissions and fugitive dust than mechanical drying and filter presses. The comparative reductions in air emissions using different dewatering and handling techniques are unknown.

There may be increased costs due to:

- energy usage (solar drying has zero energy costs)
- equipment costs
- labor costs

3.3 Operating Practices - Closure

3.3.1 Dewatering

Using a different method for dewatering waste during the closure process can alter the amount of air emissions. Pressurized liquid pumping and disposal with the gases remaining entrained is a way to contain emissions. Rapid dewatering can limit biological and chemical production of gases. This can be accomplished by chemical fixation or sorption using soil, cement, or crushed coral (EPA, 1982).

If additional equipment is needed, there will be additional costs for capital, installation, maintenance, labor, and other associated costs. Materials, if used for rapid dewatering will increase the cost of closure.

3.3.2 Proper Consolidation

Proper consolidation before final cover reduces settling. Differential settling can cause the disruption of the integrity of the cover leading to uncontrolled emissions of gases from underneath the cover. Settling may be significant if remaining wastes are high in organic content or if organic sorbents are used to solidify the wastes. Inorganic chemical fixation processes are not prone to significant settling (EPA, July 1982). Wastes should be compacted as much as possible before installation of the final cover. This would reduce the possibility and extent of settling once the cover is installed.

3.3.3 Fugitive Dust Abatement

There are two common control techniques to reduce fugitive dust emissions: wetting and stabilizing. Wetting is the application of water as a short-term method to control dust in a confined site. Stabilization methods isolate dust sources from wind erosion and may be physical, chemical, or vegetative. Physically, a cover of stabilizer materials, e.g., rock, soil, crushed or granulated slag, bark, and wood chips, prevents the wind from disturbing the surface particles on the impoundment. Chemical stabilization involves the use of binding materials that cause smaller dust particles to adhere to larger surface particles. Many types are available, many of which are proprietary developments. They are applied in conjunction with water or separately. Most stabilizers work for a limited period of time, in general, no more than a few months. Vegetative stabilization provides permanent dust suppression, but the surface must be well prepared with fertilizers, organic matter, etc. Vegetative stabilization is not applicable to fugitive dust abatement during closure (EPA, 1982).

The effectiveness of wetting and stabilizing techniques are highly variable and depend greatly on site specific characteristics. Generally, these techniques would not be frequently applied during excavation since surface impounded waste materials usually possess sufficient moisture. Efficiencies also depend on the type of stabilizer used. Chemical stabilizers are extremely variable and particularly difficult to evaluate because of proprietary information. More information on fugitive dust statement is given in the section on waste piles.

Wetting is a cheap short-term method of dust control. Physical covers have high associated costs in their application, particularly if transportation is required. The costs of chemical stabilizers are variable.

4. In-situ Controls

Technologies applied at an impoundment site during the active phase of its lifetime can be used to change one or more of the parameters that affect emission rates from the surface of the impoundment. Some of these parameters are exposed surface area, wind speed, mass transfer coefficient, etc. The in-situ technologies described below are: rafts, barriers, shades, floating spheres, and surfactant layers.

4.1 Rafts

Rafts reduce the surface area. They must be designed to remain afloat and must also be kept from being flooded by waves on the surface of the impoundment. Flexible membrane covers may be made into rafts by attachments on to a frame that is sufficiently high to keep the raft from being flooded. However, the higher the frame, the more wind the raft catches, and therefore, the stronger it has to be structurally.

A "moat raft" consisting of a small frame inside a large frame with the frames connected at the corners is a design that can reduce wind shear and also reduce flooding. The inner frame is membrane-covered and serves as the vapor barrier. The open area between the 2 frames traps the waves and prevents flooding (Cluff, 1967).

Rafts may lead to an increase in the temperature of the impoundment and thus a reduction in their effectiveness. A highly reflective top surface, for example, a surface of aluminum bonded to polyethylene or Styrofoam painted white on top would help in mitigating this problem. Crow (1973) showed that unpainted Styrofoam with 48 percent coverage reduced evaporation by 35 percent. When the top was painted white, a 45 percent coverage gave a reduction of 43-49 percent. Styrofoam not only floats and sheds rainwater but serves as insulation on the surface of the impoundment. Experiments have shown that one-inch thick Styrofoam panels significantly reduced daily variation in stored thermal energy (Crow, 1973).

Floating covers or rafts have been used on small water reservoirs to reduce evaporation. These rafts are small (around 8 feet by 8 feet) and can fit any size or shape reservoir. They are easy to install and do not have to cover the entire surface of the pond. A raft can be made of any kind of material. Styrofoam, polyethylene, aluminum bonded to polyethylene, butyl rubber, and floating concrete (made from cement, sand, and Styrofoam) have all been field tested. When used on a hazardous waste impoundment, the raft material would have to be chemically compatible with the waste components.

Another raft system uses floating covers of foamed glass blocks coated with fluoropolymer which have been used to reduce tank emissions and to maintain tank temperature. The blocks used in one case were rectangular, 2 inches thick, with 10 mils PTFE fluoropolymer coating, 9 x 18 inches and 12 x 18 inches in the main area of the tank. The purpose was to reduce sulfuric acid emissions. Triangular blocks were used to fill in the curved portions of the tank surface. The fluoropolymer coating was applied by a spray and bake process and gave a non-wetting surface with a low coefficient of friction. This surface was also chemically resistant to most organic and inorganic acids, solvents, salts, and mild caustics at temperatures up to 500°F. The glass blocks and coating are custom designed and commercially available. This technology can be easily adapted for hazardous waste applications. The size and shape of the blocks to be used depend on the configuration of the tank or impoundment surface. The coating to be applied on the blocks depends on the chemical characteristics of the waste contained in the tank. The cellular glass insulation blocks are made by Pittsburgh Corning and the coating was a proprietary process of W.L. Gore and Associates, Inc., Coatings Division (Sandberg et al, 1983). W.L. Gore does not presently provide the coating process (Personal Communications, June 1984).

The parameters that determine the effectiveness of rafts are:

- percent of surface covered. Crow (1973) demonstrated that the reduction in evaporation from small reservoirs was approximately directly proportional to the percent of pond area covered.
- wind speed over impoundment. Very high winds may cause rafts to be blown off the impoundment. Winds cause waves on the impoundment surface which might flood the rafts.
- chemical compatibility of raft material with waste.
- insulating capacity of rafts. This is related to thickness of raft and color of raft surface.

One inch thick white Styrofoam rafts covering 45 percent of a pond containing water reduced evaporation by 43-49% (Crow, 1973). It would be reasonable to assume for a surface impoundment, as in a water pond, that the percent reduction of emissions is proportional to the percent area covered by rafts. Also, assuming that diffusion is zero through the covered area, percent reduction emissions equals the percent of the area covered.

Rafts can be designed to fit any size or shape impoundment. They are also very easy to install.

4.2 Barriers

The main purpose of barriers is to serve as wind-breakers over the surface of an impoundment and thus reduce the mass transfer coefficient. They can be used in conjunction with other in-situ controls or by themselves as a means of reducing evaporation. Various kinds of barriers have been field tested in small reservoirs:

- open-picket baffles which basically consist of a picket-type snow fence supported by floats. The floats can be adjusted for different barrier heights, varying the ratio of the barrier spacing to the barrier height (L/H).
- closed wind barriers which consist of a picket fence with flexible membrane linings fastened to the pickets.
- Styrofoam barriers consisting of Styrofoam strips joined to form a grid over the impoundment surface. No floats are necessary (Crow and Manges, 1967).

The parameters that determine the effectiveness of barriers as a means of minimizing wind over an impoundment surface and as ways of reducing emissions through vaporization are:

- the higher the barrier, the more effective it is as a wind breaker. Within a certain range, the ratio L:H should be small for greater effectiveness. However, the higher the barrier is, the stronger it has to be structurally.
- chemical compatibility of waste with barrier.

Costs would vary with material used to construct barriers, the dimensions of the barriers, and the size of the impoundment (surface area to be controlled).

Barriers are usable with other technologies, for example, rafts and floating spheres.

4.3 Shades

Shades serve as wind-breakers and also reduce solar irradiation over the surface of an impoundment. Shades have been tested in small water impoundments. In field tests, mesh shades made of polypropylene were stretched tightly slightly above impoundment surface (Crow and Manges, 1967). Other materials may also be suitable.

The effectiveness of a shade in reducing emissions through evaporation is dependent on the shade value (see Table III-1). The higher the shade value of the mesh shade, the greater the reduction in emissions. Crow and Manges (1967), found an evaporation reduction of 35 percent from a small reservoir using a polypropylene mesh of 6 percent shade value, 12 mesh per inch, and 0.95 density. When used together with a chemical film, the reduction was increased to 46 percent.

TABLE III-1

EVAPORATION SUPPRESSION BY SHADES

Material Tested	Evaporation Reduction (percent)
Polypropylene Mesh 6 percent shade (natural)	26
Polypropylene Mesh 47 percent shade (black)	44

Source: Crow and Manges, 1967

The work by Crow and Manges was performed on water reservoirs. Evaporation from water surface is entirely gas-phase controlled and is quite sensitive to surface temperature. Volatilization from organic contaminated impoundments is generally liquid-phase controlled, as has been noted above. In this circumstance, the mass transfer is less strongly coupled to temperature. Thus, the effectiveness of shades may be lower for hazardous waste containing impoundments.

4.4 Synthetic Covers

A synthetic membrane cover over an impoundment reduces air emissions by reducing wind over the impoundment surface and by containing the emissions so that they can be treated further, if desired. One such cover system has been installed in September, 1983 over an aerated lagoon belonging to Upjohn, Inc. in New Haven, Connecticut. The lagoon (425 feet x 150 feet and 8 feet deep) has two 75 hp aerators and 25 7.5 hp floating aerators. Bacteria is added every day and also recycled from the clarifier. The air is maintained at 19 percent oxygen using 3 different fans. Exhaust is through either one of 2 carbon adsorbers installed at the vent outlet. The carbon adsorbers are steam regenerated every 2 days, and the condensate is recycled back to the lagoon to be further biodegraded.

The air structure at Upjohn is made of a vinyl-coated polyester membrane which is coated with Teflon on the inside. It is harnessed to the foundation around the impoundment by cables. The influent COD is 5,000 ppm and the effluent contains 700 ppm in solution. The structure was installed due to odors from the lagoon. Since installation, odor complaints have been decreased significantly (Upjohn Chemical Company, New Haven, Personal Communications, April, 1984).

A similar structure without a recovery system was installed in the fall, 1983, over glauber salt storage ponds used by American Natural Gas in Beulah, N. Dakota, to keep precipitation out. This company has two ponds that are alternately used. The air structure is movable from one pond to the other. The air structure covers around 2 acres and is made of vinyl reinforced material over a concrete foundation. Two air blowers are used to keep the structure inflated. The facility is totally enclosed except for one vent and a door for exit and entrance. Another ground-mounted, air-supported structure to be installed in Livingston, LA, by CECOS to keep precipitation out is the CECODOME, expected to be completed in September, 1984.

The Upjohn air structure cost around $400,000 with installation included. The various appurtenances (carbon adsorbers, fans, etc.) cost around $100,000. Up to the present time, total expenses are in excess of 0.5 million (around $600,000). Further expenditure is expected on roads, and other related expenses (Upjohn Chemical Company, Personal Communications, April, 1984). The American Natural Gas installation cost around $300,000 without installation and $400,000 including installation.

4.5 Floating Spheres

Hollow plastic spheres have been used in many applications in industry as a barrier to evaporative energy losses and also to reduce the generation of air pollutants in the work environment. These spheres have also been used for other purposes, for example, in the reduction of oxygen absorption, prevention of erosion and corrosion, etc. These spheres have been used for almost 20 years in industry throughout the world.

On a liquid surface that is completely covered with hollow spheres, each ball touches its six neighbors. The ratio of area covered by the balls to that not covered is independent of the ball diameter, 91 percent. Because the balls are hollow, they act as dead air space insulators. The spheres are designed with an anti-rotation collar which locks the spheres in place and prevents the turning of spheres which would expose the wet surfaces.

The hollow spheres are available in polypropylene and high molecular weight polyethylene. The sizes of the spheres are 20 mm (3/4 in), 38 mm (1½ in), 45 mm 1-3/4 in), and 150 mm (6 in) in diameter. Only the 45 mm is available in polyethylene. The balls are simply poured onto the surface of the liquid until it is completely covered. The approximate number of spheres required for an application is shown in Table III-2.

A cover of touching floating spheres reduces emissions proportionally to the area covered by the balls. The percentage area covered when a layer of spheres fills the surface is independent of the size of the spheres used. The maximum covered area is approximately 90 percent. Experimentally, evaporation from an open insulated tank containing water at 80°C was reduced by over 88 percent when a blanket of balls was used. Assuming that diffusion through the balls is negligible compared to the uncovered portions of the surface, the percent reduction of emissions when compared to a totally open surface is equal to the percent area covered. Adding another layer of spheres only marginally decreases the emissions from a surface relative to a single layer.

Normally, one layer of balls is sufficient. More layers may be used. However, the usefulness is limited when the bottom layer becomes submerged under the liquid surface. Using different size balls does not increase the effectiveness of the layer since a random array will be formed. The choice of the size of spheres depends on size of tank and its configuration. Because the maximum coverage, around 90%, is independent of the size of spheres, all blankets are equally effective.

TABLE III-2

SPHERE REQUIREMENT PER UNIT AREA AND VOLUME

	20 mm (3/4 in)	38 mm (1½ in)	45 mm (1-3/4 in)	150 mm (6 in)
Quantity/m^2	2,500-3,000	750-800	500-575	45-50
Quantity/ft^2	230-280	75-85	45-55	4-5
Quantity/m^3	165,000-167,000	24,000-25,000	14,500-15,000	350-500
Quantity/ft^3	4,670-4,730	690-710	410-425	10-11

Source: Capricorn Chemicals Corporation, Secaucus, NJ, 1984

The factors involved in the choice of spheres are:

- chemical characteristics of waste.
- compatibility with waste (Capricorn Chemicals literature include a long chemical resistance table). The spheres are resistant to most chemicals.
- size of sphere.
- number of spheres required.

The installation of these spheres is simple; they are dumped on a liquid surface. The spheres rapidly arrange themselves into a regularly formed cover and will adjust themselves around obstacles in the tank. Blockage or entry of spheres into pipes, etc. may be prevented by wire cages over inlets and outlets and by selection of the correct size spheres.

Removal of the spheres can be handled by using a net that is lifted up from the bottom of a tank. The contents of the tank are always accessible since the spheres are easily moved aside and reformed into a cover. Gas mixtures cannot accumulate under the blanket. Once applied, the system requires little maintenance, attention, or replacement.

4.6 Surfactant Layers

This category includes any system in which a thin layer is used as a cover on the surface of an impoundment to reduce evaporation from the impoundment. There have been many field tests on the use of monomolecular films of long chain alcohols (hexadecanol and octadecanol) on water reservoirs. The most important consideration in the effectiveness of a monomolecular layer is the maintenance of a continuous film on the water surface. In its use in reservoirs, a monomolecular film must retard the movement of water vapor but must allow sufficient oxygen, carbon dioxide, and other gases through. It must have an ability to seal itself after it has been disturbed. Because of losses by wind and biological attrition, a monomolecular film has to be maintained by additional dispensation.

Various ways of applying the film have been tested. The chemical has been applied in liquid, solid, powder, slurry, and emulsion form, using broadcasting, wire cages supported on rafts, wick drippers, and wind-controlled dispensers.

The major factor that destroys the continuity of the film is wind. Winds greater than 10-15 mph can push a film to the downwind edge so that there is almost no coverage.

There are several considerations in transferring this technology to reducing evaporation from surface impoundments:

- Hazardous wastes are very seldom neat solutions. This complicates the search for the chemical that would work for the chemicals in a particular waste impoundment.
- The chemical characteristics of hazardous waste impoundments vary from industry to industry and from impoundment to impoundment. A chemical that is effective as a surfactant in one situation may be useless in another. It also increases the difficulty of determining a rate of application that is sufficient to maintain a continuous layer on the impoundment surface.
- The top layer of a hazardous waste impoundment may vary in composition spatially and temporally. This is especially true for active impoundments which are not in equilibrium.

The system may be effective for floating layers of organics and other situations where diffusion is normally gas-film controlled. If the layer reduces the mass transfer coefficient sufficiently to shift control to the liquid side, then the overall rate of emissions can be reduced significantly. This is the situation at the surface of water reservoirs. For dilute solutions of organics in water, the control general rests in the liquid-film. Adding additional liquid side resistance will not, in general, result in significant reductions in the overall rate of emission, although a thick floating layer of some immiscible liquid, such as mineral oil, may add sufficient resistance to be significant.

To retard the evaporation of a liquid, an adsorbed monolayer would have to be closely packed at the liquid-air interface. Bernett, et al (1970) tested some soluble surfactants and some slightly soluble or insoluble surfactants on toluene, 2,2,4-trimethylpentane, and nitromethane and concluded that the evaporation rate of these liquids was not significantly retarded even though the adsorbed molecules did spread spontaneously to form continuous monomolecular films. This seems to suggest that it would be difficult to find the suitable surfactant for any sample hazardous waste. Even if an adsorbed monolayer is closely packed at the surface, the rate of evaporation might not be retarded.

However, rates of evaporation may be reduced by relatively thick polynuclear films. Polydimethylsiloxanes reduced the evaporation of nitromethane by 28 percent when a film approximately 0.3 mm deep was used. Because of the low solubility of some organics in water, thin water layers may be effective as evaporation barriers. A variation of this may be aqueous foams like those used to extinguish fires (Bernett et al, 1970).

Important consideration in designing a surfactant layer system for the reduction of evaporation from surface impoundments are:

- chemical characteristics of waste.
- choice of a suitable surfactant based on the waste. This is most likely to be best resolved by tests with the actual waste on the top of the impoundment.
- thickness of surfactant layer. This factor may not be significant. McCoy (1982) found that the rate of evaporation is independent of layer thickness. The thicker the layer, the more effective it is likely to be, although there is probably a critical thickness above which the marginal reduction of evaporation is very insignificant.
- wind speed over the impoundment.
- temperature profile in the impoundment. The use of a layer over an impoundment is likely to increase the temperature on the top of the impoundment and change the temperature gradient in the impoundment (Bartholic, 1967). This would somewhat decrease the actual evaporation reduction when compared to expected effectiveness.

The cost of using surfactant layers depends on the surfactant, the rate of application, the equipment and labor requirements.

As mentioned above, the effectiveness of a surfactant layer is dependent on the ability to maintain a continuous film. This means that a surfactant layer would not be very effective on an aerated impoundment since the surface is continually disturbed. This technology looks simple at the outset, but the choice of an effective surfactant would be a much less simple matter, considering the complex nature of hazardous waste impoundments. Surfactant layers are not included in further discussions of in-situ controls because of these uncertainties and possible limited applicability in surface impoundments.

5. Post-Treatment

As discussed above in the section on synthetic membrane covers, collection and post-treatment of emissions have been used by at least one facility, Upjohn in New Haven, Connecticut. In this case, an air structure with a vent and post-treatment using regenerative carbon adsorption was used.

Basically, a post-treatment control requires a means of collecting the emissions by means of a cover and a vent, and treatment unit(s) at the vent. Other forms of treatment may be used besides carbon adsorption, including afterburning and condensation. Descriptions of two approaches, carbon adsorption and afterburners follow.

5.1 Gaseous Carbon Adsorption

Removal of volatile compounds from a gas stream by adsorption is a widely used process. Adsorption is a process in which the volatile components retained on the surface of granular and highly porous solids. Activated carbon is most commonly used as the adsorbent, although other materials are available for specialized applications. In the process, the gases to be treated are sent through a bed of adsorbent. The components to be removed adhere to the surface of the grains and, in addition, diffuse into and are trapped in the pores of the material.

The process can be reversed so that both the adsorbent material and the vapors that have been retained may be recovered. Carbon adsorption systems are available as complete package units from several manufacturers. These units can be installed with the minimum of on-site operations. Custom designed systems are also available for larger or special purpose applications.

The cost per unit quantity treated is generally considerably less in a regenerative configuration than in a non-regenerative system, even though the capital costs are higher for the former type. If the recovered material can be reused and has a high market value, recovery in carbon adsorption systems can produce positive cash flow. If the recovered material, on the other hand, has value only in terms of the heat content used as a fuel, then the overall costs will generally be higher.

In hazardous waste applications, particularly at commercial facilities which receive a wide variety of wastes, the recovered materials would not be expected to have appreciable market or fuel value. In this case generation and recovery will be considerably more expensive. If the recovered organic wastes must be subsequently disposed of by incineration or even by land disposal, then the overall costs may approach those of operating in a non-regenerative mode. Although the capital costs of non-regenerative systems are smaller than those which recover carbon and adsorbed materials, cost per pound of material removed are very much higher because large quantities of expensive carbon adsorbent would be required.

Adsorption is a very effective process. When gases containing organic vapors first contact fresh adsorbent the vapors are quickly and efficiently removed from the gas stream. Efficiencies of up to 95% are commonly achieved. As the gas being treated continues to flow over the bed of carbon, its adsorbtive capacity gradually decreases. At some point, the adsorbent will become saturated and no materials will be removed. In operating systems, the process is stopped before this point, called the breakthrough point, is reached and the carbon is either replaced or generated. Regenerative systems employ multiple beds so that gases can be continuously treated while one of the beds is being replaced or regenerated. Alternate approaches use moving bed adsorbers in which fresh carbon is continuously replaced. Spent sorbent is removed at one end of the system, passes through the regenerator, and is replaced at the gas inlet end. This type of system, in theory, has a more efficient utilization than does a fixed bed system using alternate units. Moving bed adsorbers are more expensive to construct and operate and more difficult to maintain.

In conventional treatment applications, carbon adsorption is generally more economical than the technique described below, incineration, at low concentrations below about 100 ppm. In applications for the recovery of volatile emissions from hazardous wastes, the economics may be reversed if the costs of secondary disposal of the recovered waste components is included. Incineration destroys the materials and no further disposal costs are required. If the recovered materials can be returned to a treatment system, then the carbon adsorption may retain its advantage for very dilute gases.

5.2 Afterburners

Afterburners are also called vapor incinerators because they are used to incinerate gases and vapors. Sources of information used in this description are Ehrenfeld and Bass, 1983; USEPA, 1978; USDHEW, 1970. Dilute concentrations of organic vapors are burned together with additional fuel to generate a high temperature of up to 870°C. The fuels used include natural gas, LPG, and distillate and residual fuel oils. Incoming gases and vapors are decomposed and oxidized as they pass through the afterburner. Combustion products include carbon dioxide, water and others, depending on the composition of the incoming gases. The residence time at temperatures less than 870°C is between 0.5 to 1.0 seconds. Generally, afterburners should only be used on those pollutants that will not produce undesirable oxidation products.

Lower oxidation temperatures may be obtained with the use of a catalyst. Catalytic afterburners operate at temperatures of between 540 to 870°C, although most combustion catalysts cannot be operated at temperatures greater than between 540 and 650°C. Catalysts used include platinum, platinum alloys, copper chromite, copper oxide, chromium, manganese, nickel, and cobalt. When a catalyst is used, care must be taken to prevent poisoning of the catalyst by limiting the concentration of incoming organics to prevent overheating of the catalyst. Most combustion catalysts cannot be operated at temperatures greater than 540 to 650°C. The maximum concentration of volatile organic carbon is limited to 25 percent of the lower flammability limit. Catalysts begin to lose their effectiveness as soon as they are used and need to be replaced when they are worn out. Catalyst life is usually between 1 and 5 years.

Afterburners can be operated with a heat recovery system. The hot combustion gases can be used to preheat process gases entering the afterburner. Less simple is secondary heat recovery with heat exchangers to transfer the heat energy elsewhere.

In designing an afterburner system, the following parameters must be specified:

- gas and vapor volume, both average and extremes, also variations due to changes in seasonal temperature.
- identify of contaminants in gas.
- concentration of contaminants in gas stream.
- expected destruction efficiency of the afterburner, from bench or pilot tests.

Afterburners can be designed to handle a range of gas inflow rates. The constituents of the gas stream must be restricted to those that will not produce undesirable combustion products, and must also not contaminate the catalyst if catalytic oxidation is used. If corrosive oxidation products are formed, the afterburner may have to be constructed from special materials. The contaminants in the gas stream must be destructible to required efficiencies at the operating temperatures and residence time of the afterburner.

The efficiency of an afterburner system depends on:

- residence time of the gases in the combustion process; the efficiency increases with residence time for times less than 1 second.
- temperature of combustion; efficiency increases with temperature.
- degree of mixing of chamber; efficiency increases with flame contact and oxygen concentration.
- nature of waste gas.
- concentration of contaminants in waste gas.
- catalyst type in the case of a catalytic process.
- active surface area of catalyst which depends on how long the catalyst has been used.

Organics have been destroyed at efficiencies greater than 98 percent with well-designed and properly-operated afterburners.

The afterburner is a well established method for destroying volatile organics. It is a conventional and well-demonstrated technology. In its use in hazardous waste applications, the changes in gas flow rate and composition may decrease the operating efficiency of the afterburner when compared to the design efficiency.

D. Effectiveness of Surface Impoundment Controls

1. Methodology

1.1 Selection of Parameter Values

To evaluate the effectiveness of controls in reducing emissions from impoundments, waste, surface impoundment, and site (environmental) parameters necessary for quantifying emissions were defined. Some typical wastes found in surface impoundments were selected. The values of physical/chemical properties needed for calculating emissions were tabulated for the chemicals. Three sizes of surface impoundments were evaluated. The sizes were determined from WESTAT data and impoundments and the 10th, 50th, and 90th capacity percentiles were selected for evaluation. The corresponding surface areas and depths at full capacity were obtained from WESTAT data. It was assumed that the impoundments were operating at 75 percent capacity most of the time and the dimensions of exposed surface area, diameter and operating depth were calculated for symmetrical impoundments with circular cross-sectional areas. The wind speed and temperature were assumed to be 10 miles per hour and 25°C respectively.

1.2 Calculation of Mass Transfer Coefficients and Emissions

Three general types of impoundments were selected to represent the family of impoundments in use: non-aerated, aerated, and impoundments with a floating immiscible organic layer. The 10th percentile impoundment assumed not to be aerated because of its small size. Small aerated installations are treated in Chapter IV under tanks. The equations for calculating mass transfer coefficients are repeated in Table III-3.

Total emissions per hour were also calculated for each of the impoundments by:

$$Q = K_{oa} A (X_L - X^*) \text{ lb - mol/hr}$$

These emissions were calculated assuming that X_L was much greater than X^* and that $X_L = 1$. For any waste in an impoundment, X_L is much less than 1 and emissions may be calculated by multiplying the emissions calculated here by the mole fraction of waste component in the impoundment. In essence, maximum emissions are provided in this methodology.

TABLE III-3
MASS TRANSFER COEFFICIENTS
($lb\text{-}mol/ft^2\text{-}hr$)

Individual

Non-Aerated:

$$k_G = 1.1 \times 10^{-4} u^{.78} D_p^{-.11} (N_{sc})^{-.67}$$

$$k_L = 3.12\,(1.024)^{\Theta-20} u_o^{.67} H_o^{-.85} \left(\frac{D_{i,H_2O}}{D_{O_2,H_2O}} \right)$$

Aerated:

$$k_G = .00039 \frac{\rho_g D_{i,air}}{D_T\, MWi} (N_{re})^{1.42} (N_{fr})^{-.21} (N_p)^{.4} (N_{sc})^{0.5}$$

$$k_L = \frac{J\,(P_r \eta)\,(1.024)^{\Theta-20}\,\alpha\,(10^6)}{165.04\, a_v\, V} \left(\frac{D_{i,H_2O}}{D_{O_2,H_2O}} \right)^{0.5}$$

Floating Immiscible Layer:

$$k_G = 1.1 \times 10^{-4} U^{.78} D_p^{-.11} (N_{sc})^{-.67}$$

Overall

Non-Aerated:

For a dilute aqueous solution at 1 atmosphere,

$$\frac{1}{K_{oa}} = \frac{1}{k_L} + \frac{1}{k_G\,(3.47\,H)}$$ where H = Henry's Law Constant ($atm\text{-}ft^3/lb\text{-}mol$)

Aerated:

$$K_{oa} = (K_{oa})_c \frac{A_c}{A} + (K_{oa})_T \frac{A_T}{A}$$

Convective Zone

$$\frac{1}{(K_{oa})_c} = \frac{1}{(k_L)_c} + \frac{1}{K(k_G)_c}$$ where $K = 3.47H$

TABLE III-3 Continued

Turbulent Zone

$$\frac{1}{(K_{oa})_T} = \frac{1}{(k_L)_T} + \frac{1}{K(k_G)_T} \qquad \text{where } K = 3.47H$$

Floating Immiscible Layer:

$$K_{oa} = P_{vp}k_G/P_T$$

Source: Arthur D. Little, Inc.

1.3 Emission Reduction and Efficiencies of Controls

The reduction in emission rates is defined by:

$$R = Q_1 - Q_2 = K_{oa1} A_1 (X_{L1} - X_1^*) - K_{oa2} A_2 (X_{L2} - X_2^*)$$

where the subscripts 1 and 2 refer to impoundments without controls and with controls respectively.

If $(X_{L1} - X_1^*) = (X_{L2} - X_2^*)$, and assumed to be 1, i.e., the highest emissions rates, then:

$$R = K_{oa1} A_1 - K_{oa2} A_2.$$

The efficiency (E) of a control in reducing emissions is defined by $100 (Q_1 - Q_2)/Q_1$ or:

$$E = 100 \frac{[K_{oa1} A \ (X_{L1} - X_1^*) \ - \ K_{oa2} A_2 (X_{L2} - X_2^*)]}{K_{oa1} A_1 (\overset{*}{X}_{L1} - X_1 \ )}$$

For our considerations, we assume no pretreatment and that $X_{L1} = X_{L2}$ and $X_1^* = X_2^*$ and:

$$E = 100 (K_{oa1} A_1 - K_{oa2} A_2)/(K_{oa1} A_1)$$

1.4 Cost-Effectiveness of Controls

The in-situ controls for emissions reductions were compared using the cost of each percent of reduction efficiency per square feet of surface area ($\$/\text{percent} - ft^2$). Pretreatment, in-situ controls, and post-treatment were compared by considering the curves of cost per pound removed (reduced) versus pounds per year removed (reduced). Similar curves were generated for cost per pound removed (reduced) versus throughput in pounds per year. For in-situ controls, the annual cost (A) is constant, irrespective of the pounds emissions reduced (R) per year or the throughput in the impoundment (T).

In-situ:

$$A = \text{constant} = yR \ (\$/yr)$$

where y = cost per pound reduction
$y = \frac{A}{R}$ (\$/lb-reduced)

Post-treatment:

$A = F + pR$ (\$/yr)

where F = cost of collection system per year
p = cost per pound of post-treatment system
$y = \frac{A}{R} = \frac{F}{R} + p$ (\$/lb-reduced)

In terms of throughput (T) and efficiency (E):

In-situ:

$A = yET$ (\$/yr)
$y = A/ET$ (\$/lb-reduced)

Post-treatment:

$A = F + pET$ (\$/yr)
$y = \frac{F}{ET} + p$ (\$/lb-reduced)

Pretreatment costs vary between \$0.50 - \$10.00 per pound of volatiles removed (Spivey et al, 1984). In-situ, post-treatment controls and pretreatment are compared below to different pretreatment costs.

Costs for pretreatment were obtained from Spivey et al (1984). Unit material costs for in-situ controls were obtained from and estimated for the three impoundment sizes by vendors of the materials. Installation, operation and maintenance, and other costs were only compared qualitatively since these were not easily available or estimated for the in-situ technologies. Collection costs were derived from a vendor (Air Structures International, Inc., Tappan, NY). Costs for post-treatment by carbon absorption and afterburners were obtained from EPA (1982).

2. Parameters

The values of waste characteristics for typical wastes are shown in Table III-4. As may be seen from Table III-4, the values of all the waste parameters varied only within about one order of magnitude except for the Henry's Law constant and vapor pressure which ranged in 5 orders of magnitude and 3 orders of magnitude for the chemicals listed respectively.

TABLE III-4

TYPICAL VALUES FOR WASTE PARAMETERS

	Liquid Density (lb/ft^3)	Liquid Viscosity (lb/ft-sec)	Henry's Law Constant (atm-ft^3/ lb-mol)	Molecular Weight	Diffusivity in Water (ft^2/hr)	Gas Viscosity (lb/ft-sec)	Gas Diffusi-vity (ft^2/hr)	Schmidt Number	Gas Density (lb/ft^3)	ΔH_v ($\frac{Cal}{g\text{-mol}}$)	Vapor Pressure (atm)
Vinyl Chloride	56.8		1361.42	62.5					0.17	6263	3.5(25°C)
Methylene Chloride	82.8	3×10^{-4}	129.79	84.93					0.24	7572	0.46(20°C)
Trichloroethylene	91.6	3.9×10^{-4}	145.75	131.5					0.37	8315	0.079(20°C)
Benzene	54.9	4.4×10^{-4}	88.09	78.11		3.02×10^{-5}	0.29	1.71	0.22	10254	0.1(20°C)
2-Hexanome	50.6	3.9×10^{-4}		100.2					0.28		
m-Xylene	53.7	4.2×10^{-4}	83.29	106.16					0.29	9904	0.0079(20°C)
Methyl Ethyl Ketone	50.3	2.8×10^{-4}	0.70	72.1					0.20	8150	0.102(20°C)
Tetrachloroethylene	101.3	6.0×10^{-4}	132.94	165.83					0.46	9241	0.018(20°C)
Toluene	54.1	4.0×10^{-4}	105.71	92.1		3.5×10^{-5}	0.26	1.86	0.26	9369	0.029(20°C)
Ethyl benzene	54.1	4.5×10^{-4}		106.17					0.29	9309	0.092(20°C)
n-Butyl Alcohol	50.6	2.0×10^{-3}		74.12			0.27	1.88			
Bromobenzene	93.3	8.0×10^{-4}		157.02		1.9×10^{-5}	0.26	1.71	0.44	10158	0.043(20°C)
Carbon Tetrachloride	99.5	6.5×10^{-4}	368.38	153.8		6.05×10^{-5}	0.24	2.13	0.43	8272	0.15(25°C)
Chlorobenzene	69.0	5.4×10^{-4}	59.26	112.56		4.37×10^{-5}	0.24	2.13	0.31	10098	0.016(25°C)
Ethyl Alcohol	49.3	8.1×10^{-4}		46.07			0.38	1.30		9674	
Acetone	49.3		0.4	58.08	6.23×10^{-5}					7642	
Average	66.33	6.05×10^{-4}		100.08	6.23×10^{-5}	3.77×10^{-5}	0.28	1.82	0.30	8872	
Highest	101.3	2.0×10^{-3}		165.83		6.05×20^{-5}	0.38	2.13	0.44	10254	
Lowest	49.3	2.8×10^{-4}		46.07		1.91×10^{-5}	0.24	1.30	0.17	6263	

Diffusivity of oxygen in water at 18°C, $(D_{o2,\ H_2O}) = 6.59 \times 10^{-5}\ ft^2/hr$

Source: Arthur D. Little, Inc.

The impoundment sizes chosen are shown in Table III-5. The values for site and impoundment parameters are shown in Table III-6. Small impoundments are usually not aerated, and so the impoundment at the tenth percentile is considered to be a non-aerated impoundment only.

3. Mass Transfer Coefficients and Emissions

The average, high, and low values for waste parameters from Table III-4 were substituted into the relationship for individual mass transfer coefficients. It was found that individual mass transfer coefficients did not vary greatly with changes in values of waste characteristics (within only about one order of magnitude). Since the primary interest is relative emissions under different control situations, the average values for the waste characteristics given in Table III-4 were used to define "typical" individual mass transfer coefficients.

The calculated individual mass transfer coefficients for non-aerated impoundments, aerated impoundments, and impoundments with a floating immiscible layer are shown in Table III-7. These values may be used for most wastes with errors within one order of magnitude.

Overall mass transfer coefficients and emissions, for $X_L = 1$, are shown in Table III-8 and III-9 respectively for a range of Henry's Law Constant and vapor pressure. In non-aerated impoundments with H much less than around 0.1 atm-ft^3/lb-mol, the waste volatilizes slowly at a rate dependent on H. The gas-phase resistance dominates over the liquid- phase (i.e. gas-phase controlled). For H much greater than 0.1 atm-ft^3/lb-mol, the volatilization is liquid-phase controlled and reaches a maximum of k_L for wastes with very high H. From Table III-4, very few chemicals have low values for Henry's Law Constant. The values for acetone and methyl ethyl ketone are around 0.5 atm-ft^3/lb-mol. 3-Bromo-1-propanol and dieldrin are very non-volatile compounds with Henry's Law Constant around 8×10^{-3} atm-ft^3/lb-mol (Lyman et al, 1982) and their volatilization is gas-phase controlled and dependent on Henry's Law Constant.

Emissions were calculated using a mole fraction of 1 of the volatile component in the impoundment. Using a median Henry's Law Constant of 100 atm-ft^3/lb-mol and median vapor pressure of 0.07 atm, the emissions without controls from aerated impoundments are the highest. The non-aerated emissions shown appear to be higher than those from floating-immiscible-layer impoundments. In reality however, the mole fraction of a waste component in an aqueous impoundment will be very low and emissions from non-aerated impoundments will be lower.

4. Emissions Reduction and Efficiencies

The parameters that control K_{ca} values in non-aerated impoundments are temperature, wind speed at surface impoundment, diameter and the effective depth of the impoundment. For aerated

TABLE III-5

SURFACE IMPOUNDMENT SIZES

	(Full Capacity)			(75% Capacity)		
Percentile	Capacity (ft^3)	Surface Area (ft^2)	Depth (ft)	Volume (ft^3)	Surface Area (ft^2)	Depth (ft)
10%	1,340	600	5	1,005	482	4
50%	73,260	2×10^4	9	54,945	16,635	7.6
90%	4×10^6	3×10^5	15	3×10^6	259,112	12

Source: Arthur D. Little, Inc.

TABLE III-6

SITE AND IMPOUNDMENT PARAMETER VALUES

Site

Wind Speed, U ft/hr	52,800
Wind Speed at Surface, $U_o = 0.035 \times U$ ft/sec	0.513
Ambient Temperature, θ °C	25

Impoundment (At 75%-capacity)	Percentile of Impoundments		
	10%	50%	90%
Effective pool diameter, D_p ft	24.77	145.54	574.38
Effective depth, H_o ft	4	7.6	12
Number of aerators	-	6	6
Diameter of aerator, D_T ft	-	1.97	6
Impeller rotational speed, ω rad/sec.	-	126	126
Power to impeller, P_r hp	-	15.4	100
Oxygen transfer rating of aerator, J lb-O_2/hr-hp	-	3	3
Efficiency of power conversion, η	-	.78	.78
Oxygen transfer convection factor, α	-	.825	.825
Turbulent surface area to turbulent volume ratio a_v ft^{-1}	-	.09	.0555
Volume affected by aerators, V ft^3 per aerator	-	3,119	39,710
Effective surface area of turbulent zone, A_T ft^2 (x number of aerators)	-	1,704.0	13,236.0
Effective surface area of convection zone,*	-	14931.2	245876

*Assuming that surface impoundment is operating at 75% capacity.

Source: Arthur D. Little, Inc.

TABLE III-7

"TYPICAL" INDIVIDUAL k VALUES FOR SURFACE IMPOUNDMENTS WITHOUT CONTROLS

	10%	50%	90%
Non-Aerated			
k_G lb-mol/ft^2-hr	0.254	0.205	0.177
k_L lb-mol/ft^2-hr	0.654	0.379	0.257
Aerated			
k_G lb-mol/ft^2-hr	-	0.42	1.78
k_L lb-mol/ft^2-hr	-	703.53	581.87
Floating Immiscible Layer			
k_G lb-mol/ft^2-hr	0.254	0.205	0.177

Source: Arthur D. Little, Inc.

TABLE III-8

MASS TRANSFER COEFFICIENTS ($lb\text{-}mol/ft^2\text{-}hr$) FOR SURFACE IMPOUNDMENTS WITHOUT CONTROLS

	Non-Aerated			Aerated		Floating Immiscible Layer		
	10%	50%	90%	50%	90%	10%	50%	90%
Vapor Pressure (Atmosphere)								
$7X10^{-4}$						$1.75x10^{-4}$	$1.44x10^{-4}$	$1.24x10^{-4}$
$7x10^{-3}$						$1.75x10^{-3}$	$1.44x10^{-3}$	$1.24x10^{-3}$
$7x10^{-2}$						$1.75x10^{-2}$	$1.44x10^{-2}$	$1.24x10^{-2}$
0.7						0.175	0.144	0.124
7						1.747	1.438	1.236
Henry's Law Constant ($atm\text{-}ft^3/lb\text{-}mol$)								
10^{-3}	$8.65x10^{-4}$	$7.11x10^{-4}$	$6.11x10^{-4}$	$7.87x10^{-4}$	$8.96x10^{-4}$			
10^{-2}	$8.55x10^{-3}$	$7.00x10^{-3}$	$5.99x10^{-3}$	$7.76x10^{-3}$	$8.83x10^{4}$			
0.1	$7.65x10^{-2}$	$6.00x10^{-2}$	$4.95x10^{-2}$	$6.89x10^{-2}$	$7.85x10^{-2}$			
1	0.3726	0.2474	0.1811	0.3702	0.4840			
10	0.6080	0.3598	0.2467	1.777	3.086			
100	0.6490	0.3770	0.2560	12.64	15.54			
1000	0.6534	0.3788	0.2569	48.80	27.37			
10000	0.6539	0.3789	0.2570	68.97	29.65			

Source: Arthur D. Little, Inc.

TABLE III-9

EMISSIONS FROM SURFACE IMPOUNDMENTS WITHOUT CONTROLS (lb-mol/hr)*

	Non-Aerated			Aerated		Floating Immiscible Layer		
	10%	50%	90%	50%	90%	10%	50%	90%
Vapor Pressure (Atm)								
$7x10^{-4}$						0.084	2.392	32.03
$7x20^{-3}$						0.844	23.921	$3.203x10^{2}$
$7x10^{-2}$						8.435	239.214	$3.203x10^{3}$
0.7						84.35	2392.14	$3.203x10^{4}$
7						842.05	23921.418	$3.203x10^{5}$
Henry's Law Constant (atm-ft^3/lb-mol)								
10^{-3}	0.4169	11.8276	158.3174	13.0919	232.164			
10^{-2}	4.1211	116.4464	1552.0809	129.09	2287.96			
0.1	36.8730	998.1120	12826.044	1146.17	20340.29			
1	179.5932	4115.5485	46925.18	6158.35	125410.21			
10	293.0560	5985.3450	63922.93	29560.75	799619.63			
100	312.8180	6271.4704	66332.67	210268.93	4026600.48			
1000	314.94	6301.41	66565.87	811797.76	7091895.44			
10000	315.18	6303.08	66591.78	1147329.74	7682670.80			

* Using $(X_L - X^*) = 1$

Source: Arthur D. Little, Inc.

impoundments, all the controlling parameters are aerator related except for ambient temperature and Henry's Law Constant. The temperature however, cannot be changed by in-situ control without impairing the effectiveness of the aeration treatment. Henry's Law Constant in this case can only be decreased by pretreatment and/or by limitation and exclusion of volatile wastes. The alternative is collection and post-treatment of emissions. For the impoundment with a floating immiscible layer, the vapor pressure of the volatile component in the layer and wind speed directly affect K_{oa}. The effective pool diameter inversely affects K_{oa}. Vapor pressure can be reduced by pretreatment and/or by exclusion and limitation, or by decreasing the temperature of the impoundment surface. For very non-volatile waste ($H << 0.1$ atm-ft^3/lb-mol, decreasing the temperature would reduce K_{oa} for non-aerated impoundments, but most chemicals have H greater than 0.1 atm-ft^3/lb-mol. In summary, the controllable parameters for each type of emission controls is shown in Table III-10.

The Henry's Law Constant decreases with decreasing temperature. At any temperature, the Henry's Law Constant of a compound is the ratio of the partial pressure (P) and the solubility of the compound at that temperature. The solubility could increase or decrease with temperature, but the sensitivity of solubility to temperature is not as large as that of vapor pressure to temperature which are related by the Clausius-Clapeyron equation:

$$\frac{d \ln P}{d T} = \frac{\Delta H_v}{\Delta Z RT^2}$$

where: ΔZ = 1 for ideal gas (vapor)

ΔH_v = heat of vaporization, (cal/mol)

P = vapor pressure (atm)

R = gas constant, (cal/mol-°K)

T = temperature, (°K)

Neglecting the change of H_v with temperature, the simplest solution to the above relationship is:

$$\ln P = A - B/T$$

where A and B are constants;

$$B = \frac{\Delta H_v}{\Delta ZR} = \frac{\Delta H_v}{R} \quad \text{(for ideal gases)}$$

TABLE III-10

CONTROLLABLE PARAMETERS TO REDUCE EMISSION RATES

FOR CATEGORIES OF EMISSION CONTROLS

$$Q' = K_{oa} A (X_L - X^*)$$

Parameter	Proportionality	Effective on Impoundment Type
Pretreatment		
Mol fraction of diffusing component, X_L	direct	aerated, non-aerated, float. immiscible layer
Design		
Effective depth, H_o	$H_o^{-.85}$	non-aerated
Effective pool diameter, D_p	$D_p^{-.11}$	float. immiscible layer, non-aerated
Wind Speed, U and U_o	$U^{.78}$	float. immiscible layer, non-aerated
(by increasing freeboard)	$U_o^{.67}$	non-aerated
Surface area, A	A	non-aerated, float. immiscible layer
Operating		
Temperature, Θ	$(1.024)^{\Theta-20}$	non-aerated float. immiscible layer, aerated
Wind speed, U and U_o (by increasing freeboard)	$U^{.78}$ $U_o^{.67}$	float. immiscible layer, non-aerated non-aerated
Surface area, A	A	non-aerated, float. immiscible layer
In-Situ		
Temperature, Θ	$(1.024)^{\Theta-20}$	non-aerated float. immiscible layer, aerated
Wind speed, U and U_o	$U^{.78}$ $U_o^{.67}$	float. immiscible layer, non-aerated non-aerated
Effective pool diameter, D_p	$D_p^{-.11}$	float. immiscible layer, non-aerated
Surface area, A	A	non-aerated, float. immiscible layer

Source: Arthur D. Little, Inc.

$$\ln P_1 - \ln P_2 = \frac{WH_v}{R} \quad \frac{T_1 - T_2}{T_1 T_2}$$

Using an average ΔH_v = 8872 cal/g-mol and R = 1.9872 cal/mol-°K

$$\ln \frac{P_2}{P_1} = 4465 \frac{T_2 - T_1}{T_1 T_2} \qquad (T \text{ in } °K)$$

$$\frac{P_2}{P_1} = \exp\left[4465\ (T{-}_2T_1)/(T_1T_2)\right]$$

Neglecting the sensitivity of solubility with temperature, Henry's Law Constant at T_1 is related to Henry's Law Constant at T_2 by:

$$H_2 = \frac{P_2}{P_1} \cdot H_1$$

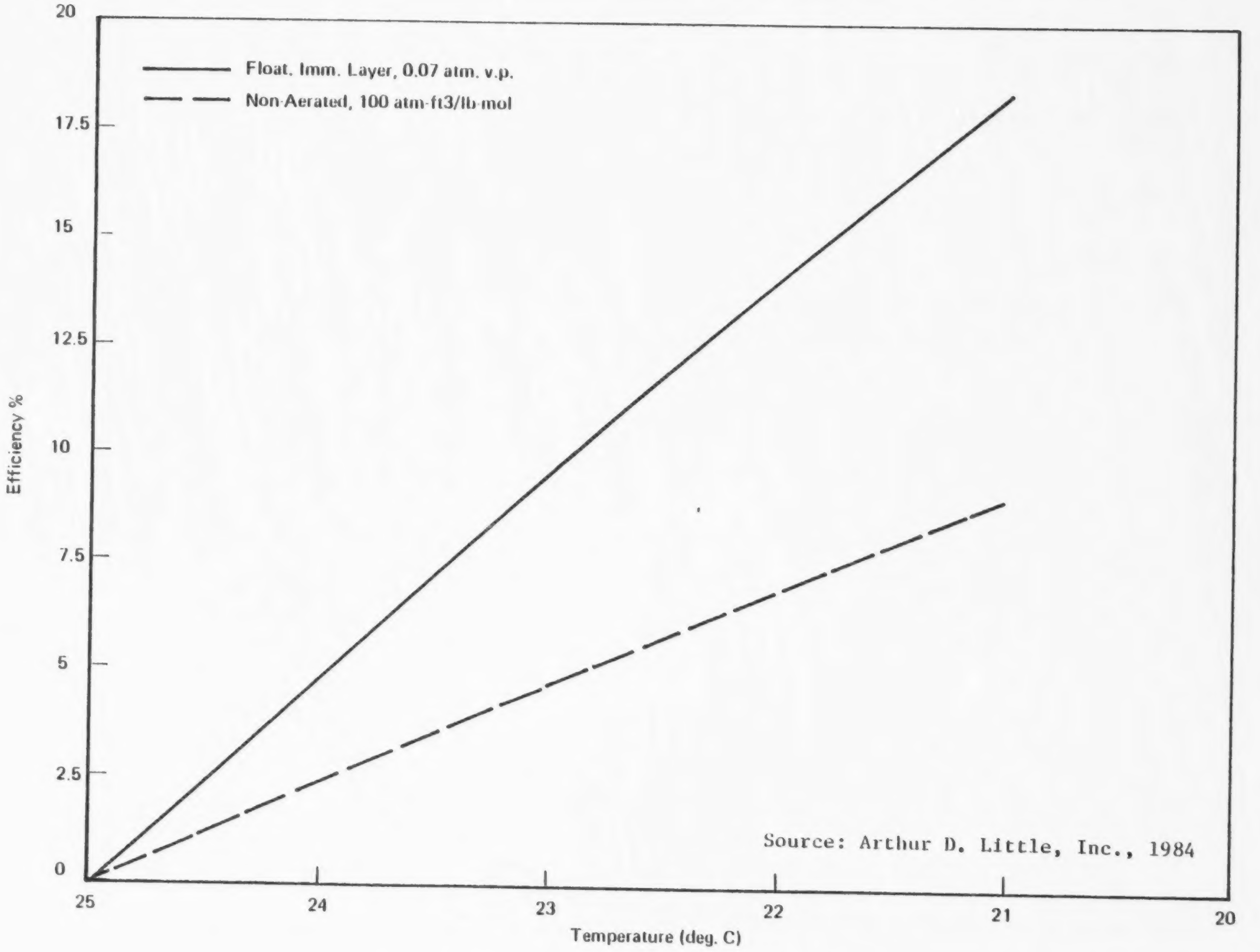
$$H_2 = H_1 \exp\left[4465\ (T_2 - T_1)/(T_1T_2)\right] \qquad (T \text{ in } °K)$$

Using the relationships of controllable parameters (temperature, wind speed and geometry) to emissions, the reductions in emissions and efficiencies of changing any of the parameters were calculated. Geometry changes were made by keeping capacity constant. The efficiencies of these changes on emission reductions from non-aerated and floating-immiscible-layer impoundments are shown in Figures III-3, III-4 and III-5 for the 50th percentile impoundment.

The figures above show efficiencies without relating them to real controls. Using the medians for Henry's Law Constant and vapor pressure (100 atm-ft^3 lb-mol and 0.07 atm respectively), emissions reductions and efficiencies were derived for each of the in-situ controls as described below. The emissions reductions and efficiencies are shown in Table III-11.

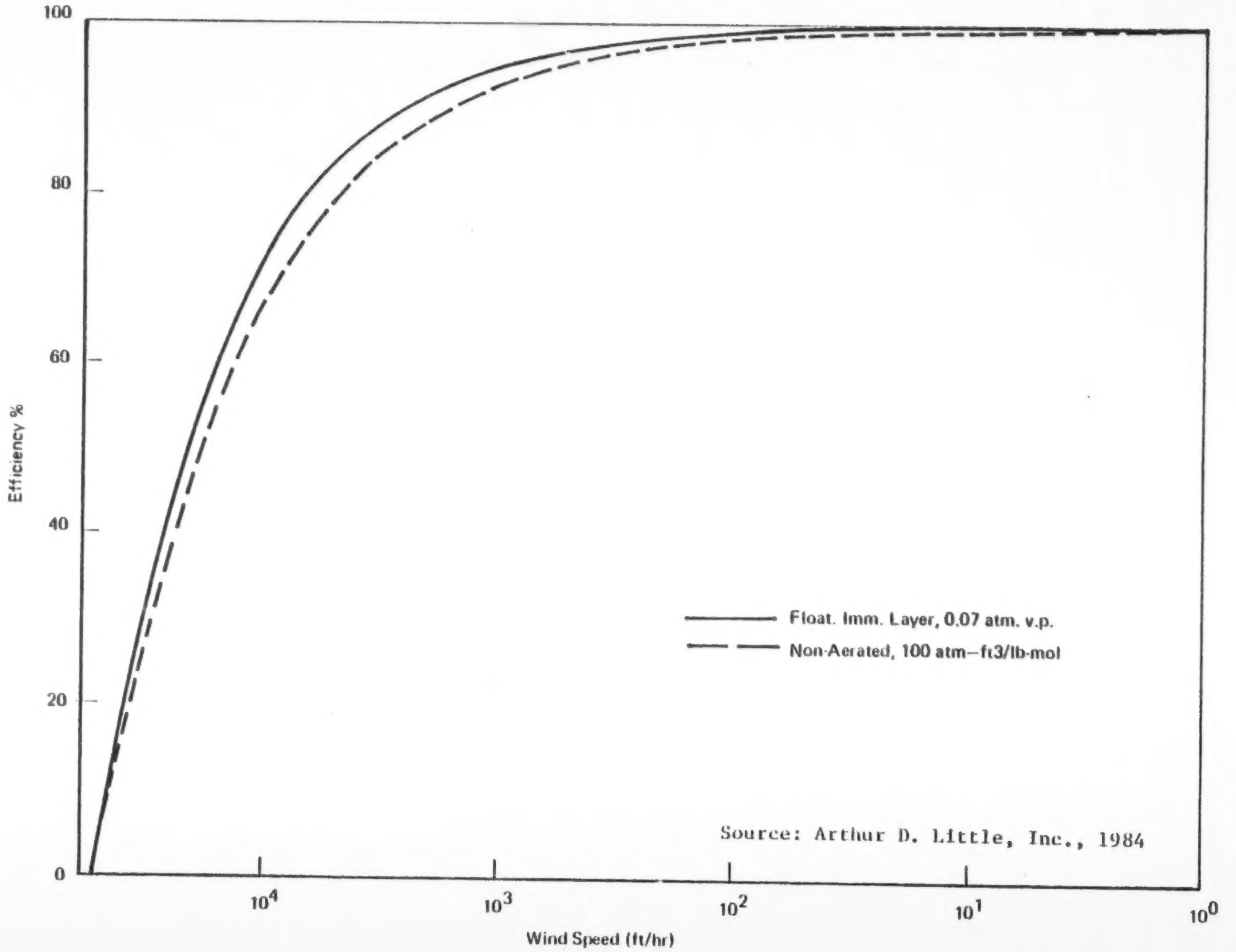
Rafts

The efficiency of rafts is approximately equal to the percent of area covered. White Styrofoam rafts 4 x 8 feet, 0.5 and 1.0 inches thick were chosen. It was assumed that 90 percent of the exposed surface area of an impoundment is covered by rafts at any time. Some



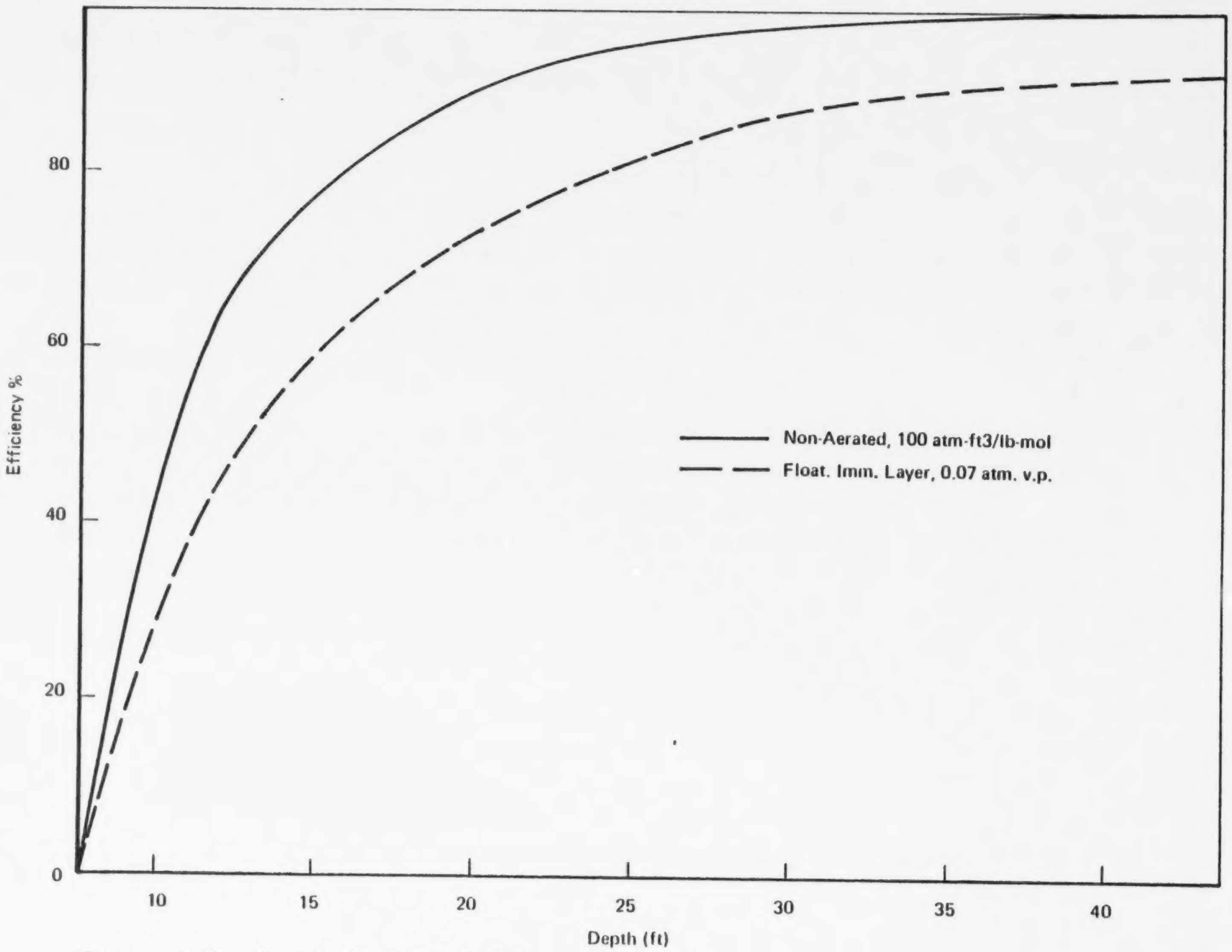
Source: Arthur D. Little, Inc., 1984

FIGURE III-3 EFFECT OF TEMPERATURE ON EMISSIONS (50th PERCENTILE SIZE IMPOUNDMENT)



Source: Arthur D. Little, Inc., 1984

FIGURE III-4 EFFECT OF WIND SPEED ON EMISSIONS (50th PERCENTILE SIZE IMPOUNDMENT)



Source: Arthur D. Little, Inc., 1984

FIGURE III-5 EFFECT OF GEOMETRY CHANGE ON EMISSIONS (50th PERCENTILE SIZE IMPOUNDMENT)

TABLE III-11

EMISSIONS REDUCTIONS AND EFFICIENCIES OF IN-SITU CONTROLS

In-Situ Controls	Reductions* (lb/yr) 10%	Reductions* (lb/yr) 50%	Reductions* (lb/yr) 90%	Efficiencies (%) 10%	Efficiencies (%) 50%	Efficiencies (%) 90%
Non-Aerated:						
Rafts	2.468×10^{8}	4.948×10^{9}	5.234×10^{10}	90	90	90
Barriers	3.017×10^{7}	6.048×10^{8}	6.397×10^{9}	11	11	11
Shades	1.207×10^{8}	2.419×10^{9}	2.559×10^{10}	44	44	44
Floating Spheres	2.468×10^{8}	4.948×10^{9}	5.234×10^{10}	90	90	90
Floating Immiscible Layer:						
Rafts	6.655×10^{6}	1.887×10^{8}	2.529×10^{9}	90	90	90
Barriers	8.134×10^{5}	2.307×10^{7}	3.089×10^{8}	11	11	11
Shades	3.254×10^{6}	9.228×10^{7}	1.236×10^{9}	44	44	44
Floating Spheres	6.655×10^{6}	1.887×10^{8}	2.527×10^{9}	90	90	90

* Using Henry's Law Constant = 100 atm-ft^{3}/lb-mol, vapor pressure = 0.07 atm, molecular weight = 100.08, $X_L - X^{*} = 1$

Source: Arthur D. Little, Inc.

of the area will be exposed due to difficulty of cutting the Styrofoam to fit the exact shape of the impoundment. The percent reduction will be assumed as 90 percent. Additional reduction may result from any effects on lowering wind relocity over the remaining open surface that are induced by the raft system.

Barriers

The reduction of wind speed over an impoundment is dependent on the height: length of grid ratio (H/L). Using flat Styrofoam (expanded polystyrene) barriers 1 x 4 inch in a 8 x 8 feet grid (i.e., H/L = 1 inch/8 feet = 1.042×10^{-2}), Crow and Manges (1967) obtained 11 percent evaporation reductions in test ponds containing water. It is likely that the efficiency of a barrier also varies with the wind speed above the influence of the barriers. An 11 percent reduction was assumed for both non-aerated and floating-immiscible-layer impoundments.

The Crow and Manges studies were carried out on water reservoirs where diffusion is controlled in the gas phase. The relative effectiveness of barriers on liquid phase controlled impoundments would depend on the difference in dependence on wind velocity in the two regimes. The exponents on the wind velocity term in the two relationships used in this study are not very different (0.78 in the gas film, Mackay and Matsuga; 0.67 in the liquid film, Owens/Hwang). To the extent that these relationships are valid, barriers for impoundments should behave similarly to water reservoirs.

Shades

The efficiency of a shade in reducing emissions from an impoundment is proportional to the percent shade of the material used, i.e., the amount of sunlight shaded out. Woven "black" polypropylene used in horticulture is chosen as the material for the shade. In pan tests, 42 percent shade black woven polystyrene mesh reduced evaporation of water by 44 percent (Crow and Manges, 1967). The reduction is due both to wind speed and temperature reduction. An efficiency of 44 percent was assumed for non-aerated and floating-immiscible-layer impoundments.

Floating Spheres

The efficiency of floating spheres is approximately equal to the percent area covered. On a fully covered surface, the covered area is 91 percent. According to vendor literature (Capricorn Chemicals), efficiencies over 88 percent have been obtained experimentally for open tanks. An efficiency of 90 percent was assumed.

Post Treatment

The rate of emissions is affected by the collection system since the collection system protects the impoundment from the environment. Emissions are drawn out of the system by fans through a vent to be post-treated.

Two post-treatment systems were used for comparison: carbon adsorption with no regeneration and afterburning. The efficiency of post-treatment control is equal to the efficiency of the post-treatment unit(s). Carbon absorption was assumed to work at an efficiency of 95 percent and afterburning at 98 percent.

5. Costs

Pretreatment

Pretreatment costs taken from Spivey et al (1984) were in the order of $1.00 per pound of volatiles removed from a wastestream ($2200/Mg). Costs for pretreatment depend on wastestream properties, treatment type, system design and size. The cost value chosen represented the range of most pre-treatment technologies within a factor of 2.

In-situ Controls

Unit material costs for various in-situ controls are shown in Table III-12. Annual costs for in-situ controls and post treatment is shown in Table III-13. These costs were obtained from and estimated for the 3 impoundment sizes by vendors of the materials. Installation costs are not included in these estimates. Relative installation, and operation and maintenance costs are given qualitatively in Table III-14. The rationale used in obtaining material, installation, and operation/maintenance costs for each technology is described below.

Rafts

Two thicknesses, 0.5 and 1.0 inch of expanded polystyrene (Styrofoam) were chosen for the costing of rafts. These rafts are expected to have a lifetime of 1 year under the conditions of usage. The installation costs are expected to be relatively low since installation is simple, involving little labor in floating the Styrofoam panels on top of the impoundment. Operation and maintenance costs are also expected to be low. Rain will slide off the top of these Styrofoam rafts. Heavy snow may cause the panels to sink, but the panels should float automatically when the snow is melted. Another element of costs is the disposal of the Styrofoam panels upon disintegration of the foam or upon closure of an impoundment. These disposal costs may be high because of the volume of Styrofoam generated which may have to be incinerated or disposed in a landfill. The disposed volumes involved per year are 40 ft^3 (10th percentile), 1,400 ft^3 (50th percentile), and 21,600 ft^3 (90th percentile) if 1-inch thick Styrofoam panels are used.

TABLE III-12

UNIT MATERIAL COSTS FOR SURFACE IMPOUNDMENT EMISSION REDUCTION IN-SITU TECHNOLOGIES

(Dollars per Square Foot, Summer 1984 Dollars)

	10th Percentile ($\$/ft^2$)	50th Percentile ($\$/ft^2$)	90th Percentile ($\$/ft^2$)
EPS[1] Sheets			
Size			
4' x 8' x 1/2"	0.08	0.06	0.05
4' x 8' x 1"	0.13	0.12	0.10
EPS[1] Strips (8'x 8' grids)			
Size			
4" x 8' x 1"	0.04	0.04	0.03
4" x 8' x 2"	0.08	0.08	0.06
8" x 8' x 1"	0.08	0.08	0.05
8" x 8' x 2"	0.17	0.15	0.11
12" x 8' x 1"	0.13	0.12	0.08
12" x 8' x 2"	0.25	0.23	0.17
Shade Cloth[2]			
Percent Shade			
21%	0.07	0.07	0.07
57%	0.11	0.10	0.09
92%	0.20	0.18	0.17

(1) Expanded polystyrene
(2) Woven "black" polypropylene

TABLE III-12 Continued

UNIT MATERIAL COSTS FOR SURFACE IMPOUNDMENT EMISSION REDUCTION IN-SITU TECHNOLOGIES

(Dollars per Square Foot, Summer 1984 Dollars)

	10th Percentile ($\$/ft^2$)	50th Percentile ($\$/ft^2$)	90th Percentile ($\$/ft^2$)
Spheres			
Polypropylene			
Diameter 1 3/4 inches	6.55	5.05	4.65
Diameter 6 inches	8.69	7.50	7.50
High Density Polyethylene			
Diameter 1 3/4 inches	7.55	6.75	6.75

Sources: Reliable Plastics, Newark, NJ, 1984
X. S. Smith Company, Eatontown, NJ, 1984
Capricorn Chemicals Corporation, Secaucus, NJ, 1984

TABLE III-13

ANNUAL COSTS FOR SURFACE IMPOUNDMENT CONTROLS, $/YR (Summer 1984 Dollars)

In-Situ[*]	10th Percentile	50th Percentile	90th Percentile
Rafts	38.56 - 62.66	998.11 - 1996.22	12955.60 - 25911.20
Barriers	19.28	665.41	7773.36
Shades	53.02	1663.52	23320.08
Floating Spheres	514.00 - 682.00	13672.00 - 20305.00	196087.00 - 316270.00
Post-Treatment[**]			
Collection		24000	250000

[*] Installation, O and M, and other costs not included.

[**] Treatment costs are variable costs depending on the amount of emissions treated. These costs are discussed in the text. The costs shown here include basic structures and installation.

Source: Arthur D. Little, Inc.

TABLE III-14

RELATIVE INSTALLATION AND OPERATION/MAINTENANCE COSTS OF IN-SITU CONTROLS

	Installation			Operation/Maintenance		
	10%	50%	90%	10%	50%	90%
Rafts						
0.5 - 1 inch Styrofoam	Low	Low	Low	Low	Low	Low
Barriers						
8' x 8' grids of Styrofoam strips	High	High	High	Low	Low	Low
Shades						
Black woven polypropylene	Medium	High	High	Low	Low	Low
Spheres						
Polypropylene/HDPE	Low	Low	Low	Low	Low	Low

Source: Arthur D. Little, Inc.

Barriers

A 8 x 8 feet grid made of Styrofoam strips 4" x 8' x 1" was chosen for the costing of barriers. The barriers may be 4 inches or 1 inch high. These barriers are expected to last a year. Barriers are expected to entail relatively high installation costs because the Styrofoam strips have to be constructed into a grid formation and installed on the impoundment surface. For small impoundments, the grid is small and consists of relatively few strips. The design and installation of the grid may be relatively easy. For large impoundments, the design and installation of the grid may have to be sub-contracted and will be expensive. Operation and maintenance costs are expected to be low under normal conditions. However, strong winds may effectively destroy a grid. Heavy snow may also damage the grid. The volume of Styrofoam generated that have to be disposed is lower than in the case of rafts but is another element of the costs in the use of wind barriers.

Shades

Black woven polypropylene shade cloth used in horticulture is chosen as the shade material. There is not much difference in price within a small variation of shade value so the cost of a 57 percent shade value is used for that of a 47 percent shade value of the same material. The installation costs of shades are expected to be relatively high. For small impoundments, the shade may be stretched a few inches over the impoundment and secured at the edge. Shade cloth is sold in pieces and pieces need to be sealed together to obtain a large enough piece to cover impoundments. Larger impoundments may require the use of floats spread out over the surface of the impoundment to prevent the shade from dropping below the impoundment surface. In horticultural use, the shade cloth is used for the 3 summer months and lasts between 7-9 years. For year around use over a surface impoundment, the lifetime is estimated to be between 1-2 years. Operation and maintenance costs are expected to be low under normal conditions. However, strong winds and heavy snow may damage the shade or cause the shade to drop below the surface. The volume of shade cloth that needs to be disposed of at the end of its useful life is smaller than in the cases of rafts or barriers.

Spheres

Polypropylene spheres of diameters 1-3/4 inches and 6 inches are used to provide a range of costs for spheres. The polypropylene spheres are cheaper than the high density polyethylene (HDPE) spheres for the same size spheres and are available up to 6 inches in diameter. HDPE spheres are available in only one size (1-3/4 inches diameter). Installation costs of spheres are expected to be relatively very low. Depending on the chemical(s) present in the impoundment, spheres are expected to last a relatively long period of use. An estimated lifetime of 10 years was used to annualize costs at 10 percent per year. Operation and maintenance costs are expected to be very low, or zero. The volume of spheres that need to be disposed of per year and at the end of its useful life is much smaller than Sytrofoam barriers or rafts.

Post-Treatment

Costs for post-treatment consists of the costs for the collection system and the treatment. The collection system cost is a fixed annual cost for the design size as shown in Table III-15. This cost was estimated by Air Structures International, Inc. (Tappan, NY) for two air structures covering 17,000 square feet and 260,000 square feet corresponding to the 50th percentile impoundment and the 90th percentile impoundment respectively. The 10th percentile impoundment was too small for the installation of an air structure. The air structure for the 50th percentile impoundment was 170 feet long, 100 feet wide and 36 feet high made of translucent fabric with a cable system and anchors for support. It has an exit door and an entrance door, a 10^6 BTU heating system, a 24,000 W lighting system and a vehicle air lock system. The 90th percentile impoundment air structure was 260 feet wide, 1,000 feet long, and 75 feet high, made of translucent fabric, with cables and anchors. It has 2 entrance doors and 16 exit doors, and 2 inflation blowers and 2 auxilliary blowers. The heating system was a 12.5 x 10^6 BTU system. Costs for lighting and the vehicle air lock system were not estimated because these varied greatly depending on the requirements. Installation costs were estimated to be between $1-2 per square foot, which includes foundations. For this analysis, installation was estimated to be $1.50 per square foot. The costs shown do not include maintenance (which is low) and energy costs. Costs for the collection system are shown in Table III-15 with costs annualized at 10 percent in 10 years.

Treatment costs are variable costs dependent on the total emissions treated. To estimate the treatment cost per pound of emissions removed, a 10,000 cubic feet per minute wastestream containing 50 ppm trichloroethylene was chosen as a representative stream through the post-treatment system. The emissions through the system would be around 20,000 pounds of TCE per year. Annual installed capital costs for both carbon adsorption and afterburning were at least one order of magnitude lower than annual operating costs (EPA, 1982). Total installed costs for carbon adsorption was $87,000 compared to an annual operating cost of $870,000. Total installed costs for afterburning was $230,000 and annual operating cost was $300,000 per year. After annualization, operating costs would be the dominant cost factor. Assuming 95 percent and 98 percent efficiencies for carbon adsorption and afterburning respectively, the costs per pound of TCE removed were around $45 and $16 respectively ($100,000/Mg and $35,000/Mg). Costs for regenerative carbon adsorption systems are an order of magnitude less than non- regenerative system. Catalytic afterburners are also less expensive than non-catalytic systems. If these two types of post-treatment systems are included, the treatment costs for post-treatment would be between $5-10 per pound TCE removed ($11,000-22,000/Mg).

TABLE III-15

CAPITAL COSTS FOR COLLECTION SYSTEM FOR POST TREATMENT (Summer 1984 Dollars)

	50th Percentile	90th Percentile
Structure	70000	985000
Heating	24500	175000
Lighting	15000	Not estimated
Air lock vehicle	15000 - 24000	Not estimated
Installation	25500	390000
Total	~ 150000	~ 1600000
Annualized (10%, 10 years)	~ 24000	~ 250000

Source: Air Structures International, Inc. Tappan, NY, 1984

6. Cost-Effectiveness of Controls

Table III-16 expresses the cost-effectiveness of in-situ controls in terms of the cost per percent of reductions per square foot of impoundment. Figure III-6 illustrates these values on a graph that compares the cost-effectiveness with impoundment size. Each set of points represent the effectiveness for the 10th, 50th, and 90th percentile impoundments. The figures show some slight economies of scale. Of the in-situ controls, rafts appear to be the most cost-effective. Shades are more cost-effective than barriers in terms of the pounds of emissions reduced. Floating spheres are the least cost-effective of the in-situ controls. When installation and operation/maintenance costs are included, the relative cost-effectiveness ranking of in-situ controls will not change, because rafts have low relative installation and operation and maintenance costs. Shades and barriers have higher values for these costs but the material costs for spheres are so much higher that the relative cost-effectiveness of spheres is still expected to be the lowest.

Figures III-7 and III-8 show the hyperbolic functions relating cost per pound of emissions reduced or removed to the throughput of volatiles per year and the total pounds of volatiles removed per year respectively. The horizontal curves represent the pretreatment cost per pound of volatiles removed. There are some economics of scale for pretreatment, but these have been neglected. Each of the hyperbolic curves are at a constant annual cost of in-situ controls. The curves for post- treatment are not shown because collection and treatment costs for post-treatment are very high and are over in the top right hand corner of the figure. For the most part, the post-treatment curves do not appear within the range of the other controls.

Figure III-7 incorporates the efficiency of each control technology by considering the throughput of volatiles. On the bottom left of the figure where the horizontal lines representing pretreatment are below and to the left of the curves, pretreatment is more cost-effective. Where the horizontal curves are above the hyperbolic curves, the in-situ controls are more cost-effective. As may be seen, pretreatment is more cost-effective for small systems, i.e. low emissions reduced and low throughputs. In a medium size impoundment, at pretreatment costs of $2.00 per pound removed ($4,400/Mg) or less, throughputs of less than 1,000 lb per year would favor pretreatment. At higher throughputs of volatiles, in-situ controls are more cost-effective. In terms of throughput, rafts are still the most cost-effective of the in-situ controls and spheres are the least. Shades when compared in terms of throughput are more cost-effective than barriers. This same comparison of effectiveness applies to small and large impoundments as well. Unless pretreatment costs for a wastestream are extremely low (much less than $0.50 per lb), in-situ controls are generally more cost-effective of all the controls.

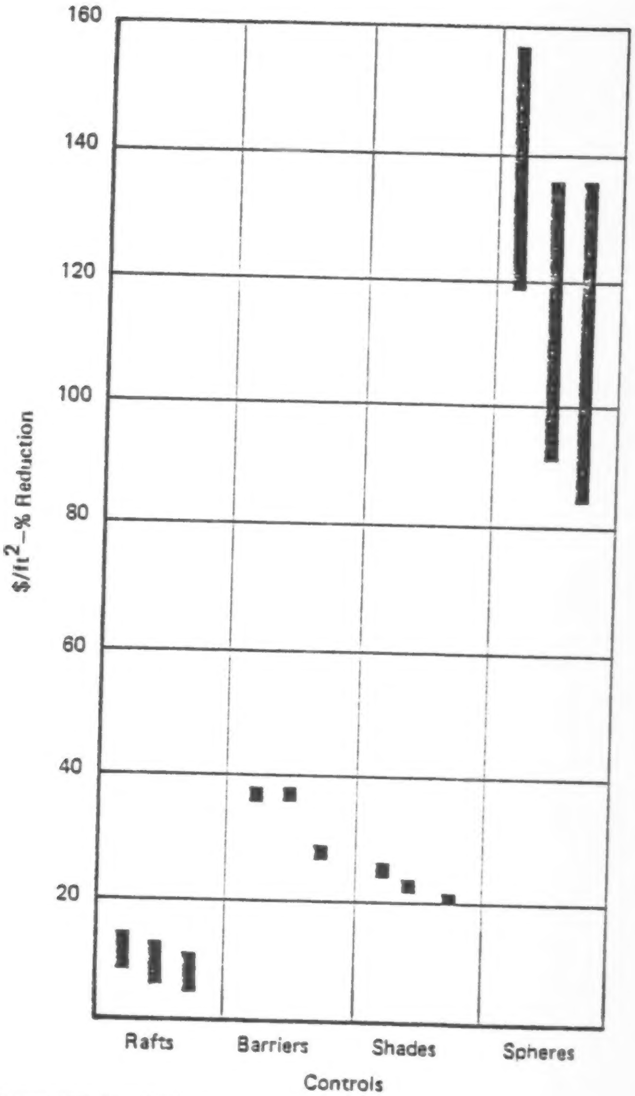
TABLE III-16

COMPARATIVE COST-EFFECTIVENESS FOR IN-SITU EMISSIONS CONTROLS

	$\frac{\$}{\%\ \text{Reduction}}$ per ft^2 (\$/ft^2)		
		$(\text{x}10^{-4})$	
Rafts	8.9 - 14.4	6.7 - 13.3	5.6 - 11.1
Barriers	36.4	36.4	27.3
Shades	25.0	22.7	20.5
Floating Spheres	118 - 157	91.3 - 136	84.1 - 136

* Without installation, O and M, and other costs; assuming rafts, barriers, and shades last 1 year and spheres last 10 years. Costs are annualized for spheres at 10 percent for 10 years. The inclusion of installation, O and M, and other costs is not expected to change the relative cost-effectiveness ranking of each technology. (Please see text.)

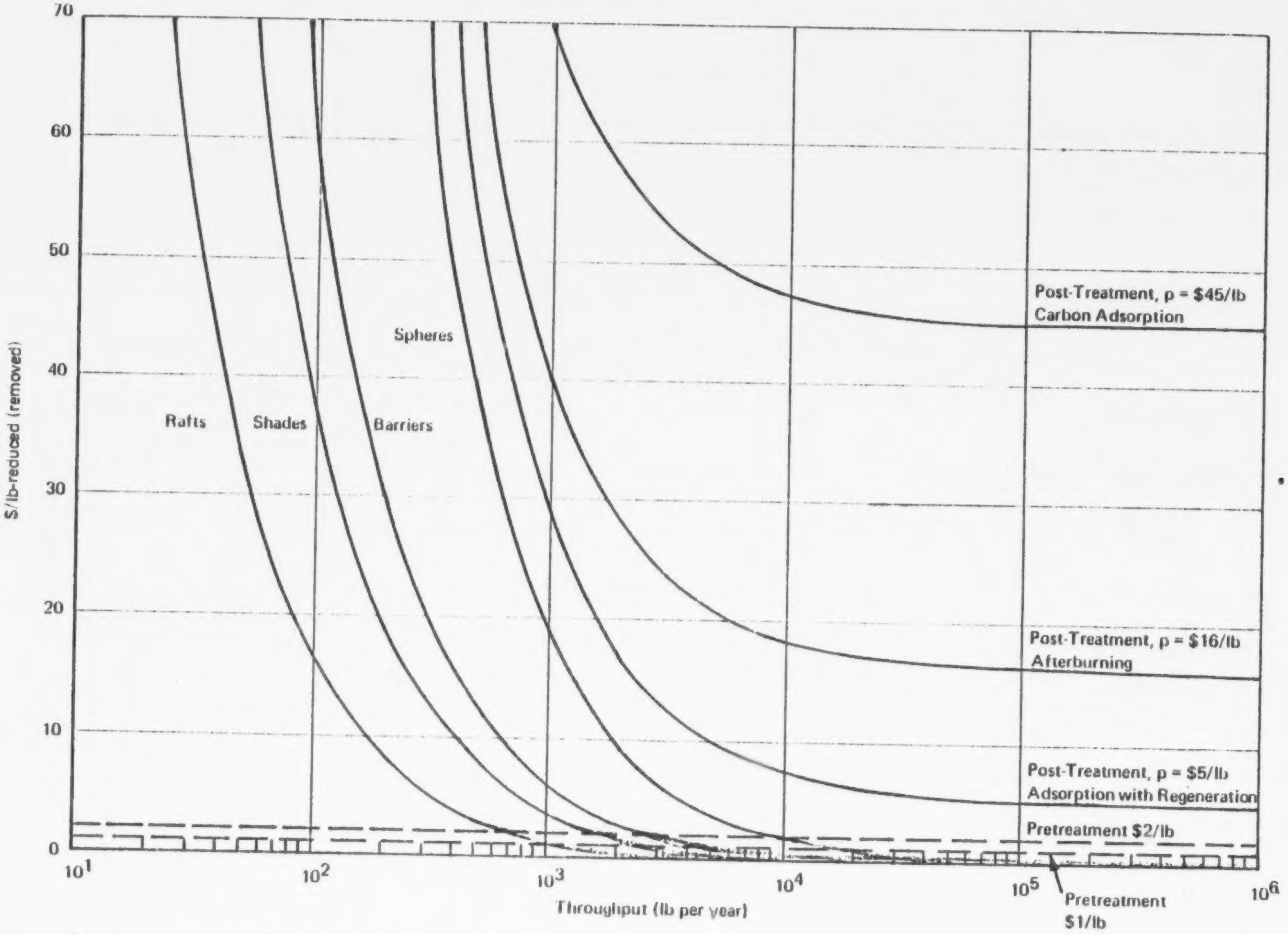
Source: Arthur D. Little, Inc.



*Only material costs are used. Installation O and M, and other costs are not included.

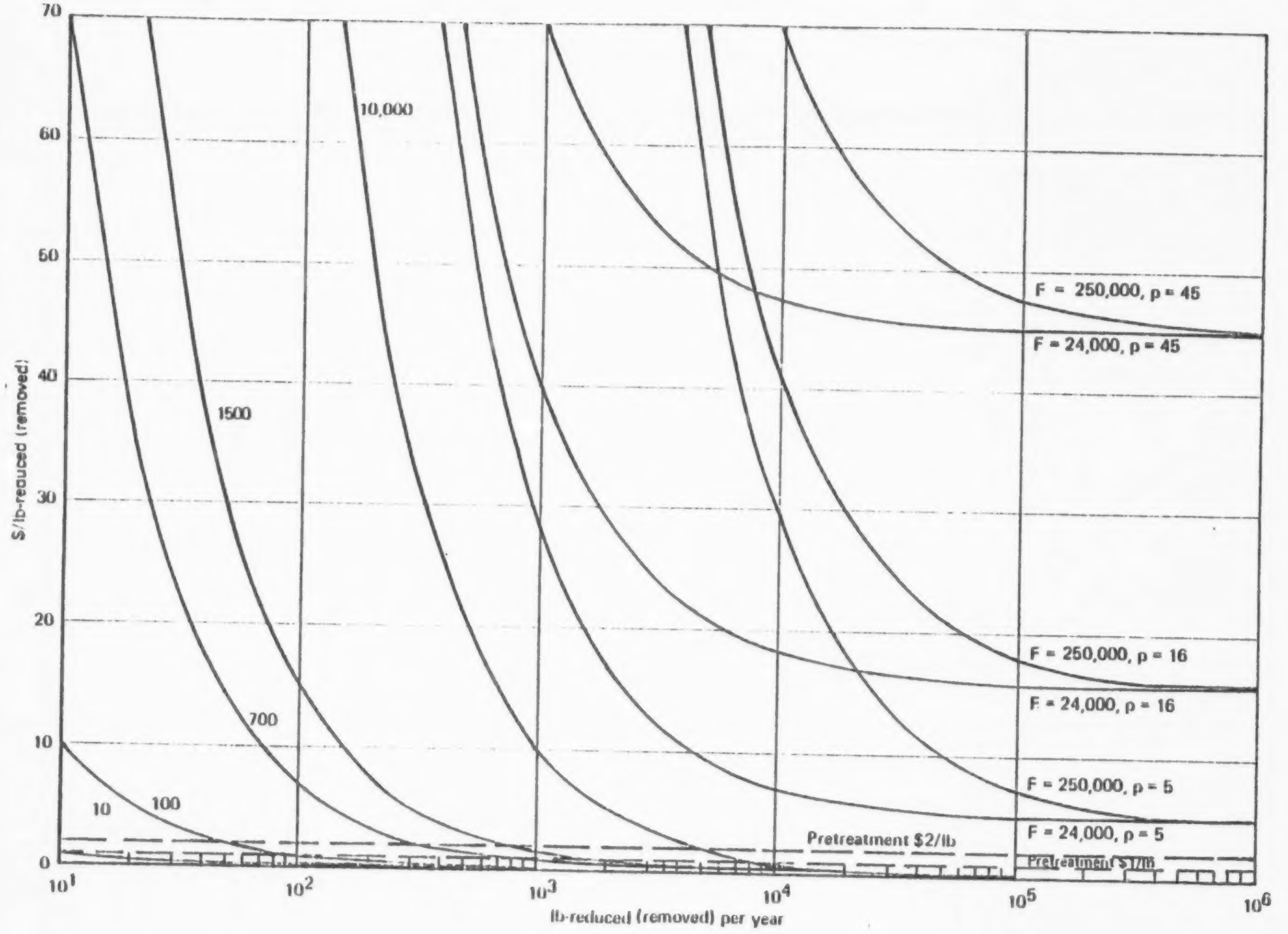
Source: Arthur D. Little, Inc., 1984

FIGURE III-6 COST-EFFECTIVENESS OF IN-SITU SURFACE IMPOUNDMENT CONTROLS*



Source: Arthur D. Little, Inc., 1984

FIGURE III 7 COST-EFFECTIVENESS OF SURFACE IMPOUNDMENT CONTROLS VERSUS THROUGHPUT (50th PERCENTILE SIZE)



Source: Arthur D. Little, Inc., 1984

FIGURE III-8 COST-EFFECTIVENESS OF SURFACE IMPOUNDMENT CONTROLS VERSUS REDUCTION

Figure III-8 shows the cost-effectiveness picture for various annual costs and a wide range of pounds of volatiles reduced or removed per year. Each of the hyperbolic curves represents an annual cost. As an example, for an in-situ system that costs $1,500 annually and if pretreatment is $1.00 per lb ($2,200/Mg), a removal rate or reduction of emissions of greater than 1,500 lb per year would favor the in-situ control. If pretreatment cost was increased to $2.00 per pound ($4,400/Mg), a rate of greater than about 800 lb per year reduced (removed) would favor the in-situ control costing $1,500 per year. The $17,000 annual cost curve which corresponds to using spheres in a 50th percentile situation illustrates the point. Floating spheres in this impoundment would be more cost-effective than pretreatment if the emissions reductions achieved was more than 17,000 lb per year and pretreatment was $1.00 or more per pound ($2,200/Mg) of volatiles removed.

E. Summary

In-situ controls are generally experimental and in many cases are taken from some other different kind of applications. For example, rafts were experimentally studied in reservoirs as evaporation controls. Spheres are more directly transferable than the other in-situ controls since they are used in emissions control from treatment tanks. On the whole, data on in-situ controls are very poor. There also appears to be limits on the use of some in-situ controls on large impoundments.

In any in-situ control, there is some point at which it becomes more cost-effective than pretreatment. This tradeoff point is very sensitive to pretreatment costs. For a small change in pre-treatment cost, the trade-off point will shift relatively far to the left (with greater pretreatment cost) or to the right (with smaller pretreatment cost). Estimates of emissions from uncontrolled surface impoundments are of the order of 800,000 metric tons per year (GCA, 1983). This reference also estimates that there are about 2,000 operating impoundments. On the average, then, emissions are about 400 metric tons per year per impoundment. At this rate, in-situ treatment should be considerably more cost effective than pretreatment.

Post-treatment, including collection and treatment is the most expensive control technique. The curves for post-treatment would fall above and to the right of the in-situ controls in Figures III-7 and III-8. If the only concern is the rate of reduction of emissions, post-treatment would never be cost-effective. However, if there is concern about the absolute level of removal, the tradeoff to be considered is between pretreatment and post-treatment. Post-treatment is more expensive than pretreatment for each pound of volatiles removed primarily because very dilute mixtures in a gaseous medium are treated. For example, for carbon adsorption assuming no regeneration, the cost per pound (not including collection) post-treated is $45. A regenerative system would cost around $5 compared with a regenerative carbon adsorption pretreatment of around $1 per pound. If, however, the waste cannot be pretreated, post-treatment may be the only way to remove volatiles even though the cost is between $10 - 50 per pound, excluding collection costs. If there is a market to encourage recovery following post-treatment, this alternative may become less expensive. Also, the post-treatment alternative may be more attractive if, as in the Upjohn case, the volatiles can be replaced in a treatment impoundment.

If the design objectives offer any flexibility, there may be opportunities to reduce emissions by altering the design of an impoundment. Operating procedures also present possibilities in emissions reduction.

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IV. CONTROLS FOR TANKS

A. Tank Description

1. Definition

Tank means a stationary device, designed to contain an accumulation of hazardous waste which is constructed primarily of non-earthen materials (e.g., wood, concrete, steel, plastic) which provide structural support (Federal Register, May 19, 1980).

2. Types, Construction and Uses

The types and construction of hazardous waste tanks are similar to those used for the storage of petroleum liquids. The types of tanks are: open tanks, fixed roof tanks, floating roof tanks, variable vapor storage tanks, and pressure tanks. The minimum accepted standard for storage of petroleum liquids is the fixed roof tank. In the hazardous waste area, open tanks are still in use. Since detailed descriptions of tanks may be found in several readily available sources (U.S. EPA, 1977; U.S. EPA, 1978; U.S. EPA, 1980; American Petroleum Institute, 1962; 1964; 1980), we will only describe them briefly here.

Open Tanks are essentially tanks without a roof. Concrete-lined basins are by definition considered tanks (Federal Register, May 19, 1980). They are examples of open tanks.

Fixed Roof Tanks have a fixed roof equipped with some type of vent.

Floating Roof Tanks consist of tanks with a roof that is free to float on the surfaces of the stored waste. External floating roofs are exposed on the surface. Internal floating roofs are covered by a fixed roof which protects the roof from the weather.

Variable Vapor Storage Tanks work by storing expanding vapors emporarily in a gas holder. Venting occurs only when the holder capacity is exceed. During periods when vapors are contracting, the stored vapors are transferred back to the storage tanks.

Pressure Tanks can withstand higher pressure variations before incurring emission losses.

Tank material, configuration and auxiliary equipment must correspond to and be compatible with the stored waste. Materials of construction include carbon steel, stainless steel, corrosion resistant alloys, aluminum, concrete, or fiberglass reinforced plastics. Tanks vary widely in configuration, fabrication techniques, materials and operating conditions. Small tanks (between 1,300 to 21,000 gallons) may be shop-fabricated. Larger tanks are field-erected (Corripio et al, 1982).

Tanks are used for two primary purposes: storage and treatment. The uses of tanks are very similar to those of surface impoundments except that tanks are not used for disposal of wastes. Besides storage, tanks are used for treatment by biodegradation, neutralization, oxidation, among many other uses.

3. Operation

The operations of a tank consist of filling and emptying. In treatment tanks, reagents may be added, and the tank may be mechanically mixed to encourage aeration. Each tank has a specified capacity for wastes depending on the design and on the volume already contained in the tank.

The frequency of filling and emptying is highly variable from tank to tank and depends on the capacity of the tank and the volume to be processed. Wastes could enter the tank with or without pretreatment. The influent could be pumped into the bulk of the waste or waste could be added from the top onto the surface of the bulk waste. The total volume of waste processed through a tank per year is called the throughput per year. The annual throughput divided by the capacity of the tank represents the number of times per year wastes are totally turned over in the tank. This factor is called the turnover rate.

At the end of their lifetime, or when operations have ceased, tanks are disassembled and disposed of.

B. Emission Sources and Models

1. General Description of Factors Affecting Emissions

Emissions to the atmosphere occur when the tank is being filled or its contents withdrawn and also while the tank is standing.

The rate of waste volatilization is dependent on the physical and chemical properties of the waste and the surrounding environment. These factors (e.g., wind speed, temperature, etc.) are similar to those affecting waste volatilization in impoundments and will not be repeated here. An open tank is similar to a surface impoundment but with a very low wind speed at the liquid surface due to the higher operating freeboard and the smaller diameter of tanks. Please refer to the discussion on impoundments for a more detailed description.

Fixed roof tank emission losses are due to:

- vapor expansion through the vent due to thermal expansion, barometric pressure changes, and/or increased vaporization (breathing losses), and

- vapor displacement due to filling and emptying (working losses).

Floating roof tank emission losses are due to:

- losses due to imperfect fit of the seal and losses through the gap between the flexible seal and the inner wall (standing losses), and

- losses due to the vaporization of the wet tank as the roof decends when the tank is being emptied (withdrawal losses).

2. Emission Models

The relationships describing emissions from tanks are described in GCA (1983). For comparison, the base uncontrolled case will consist of two different uses of open tanks: storage and aerated treatment. Each of the different roofs (fixed roof and floating roof) will be considered as a control alternative. The relationships for the latter type are empirical. The models for emission losses from open tanks are the same as those describing surface impoundments. Table IV-1 summarizes these relationships.

The definition of each of the parameters in these relationships is shown in Table IV-2.

3. Parameters That Control Emissions

The rate of emissions from an open tank depends on the overall mass transfer coefficient, the exposed area, and the concentration or mole fraction in the waste. These are the same factors that determine the rate from surface impoundments and are not repeated here.

C. Potential Controls

1. Summary of Applicable Controls

The categories of potential controls are similar to those used in surface impoundments: pretreatment, design and operating practices, in-situ controls and post-treatment. Each control will be described under these approaches in terms of their mode of action, expected effectiveness and related costs. Only those approaches not already covered in surface impoundments will be discussed in detail.

2. Pretreatment

Pretreatment basically removes the volatile components of a waste before it is put into a tank. A detailed discussion is given in the Surface Impoundments chapter.

TABLE IV-1

RELATIONSHIPS DESCRIBING EMISSION LOSSES IN TANKS

OPEN STORAGE: Please see Surface Impoundments, Non-Aerated

AERATED: Please see Surface Impoundments, Aerated

FIXED ROOF TANK:

$$\text{Losses} = Q_i = L_B + L_w$$

Breathing: $L_B = 2.26 \times 10^{-2} M \left[\frac{P}{14.7-P}\right]^{0.68} D^{1.73} H^{0.51} \Delta T^{0.50} F_p CK_c$ lb/yr

Working: $L_w = 7.56 \times 10^{-4} M P K_N K_c Q$ lb/yr

FLOATING ROOF TANK:

$$\text{Losses} = Q_i = L_s + L_w$$

Standing: $L_s = K_S V^N P^* D M K_c E_F$ lb/yr

Withdrawal: $L_w = \frac{(0.943) Q C_L W_L}{D}$ lb/yr

Source: American Petroleum Institute

TABLE IV-2

PARAMETERS FOR TANK EMISSION RELATIONSHIPS

PARAMETER	DEFINITION	UNITS
Waste:		
M	Molecular weight	lb/lb-mol
P	True vapor pressure at bulk liquid	psia
K_C	Product factor	-
P^* (also environment)	Vapor pressure function	-
C_L (also tank)	Shell clingage factor	bbl/1000 ft^2
W_L	Average organic liquid density	lb/gallon
Tank:		
D	Tank diameter	feet
H	Average vapor space height	feet
F_P	Point factor	-
C	Adjustment for small diameter tanks	-
K_N	Turnover factor	-
K_S	Seal factor	-
N	Seal related wind speed component	-
E_F	Secondary seal factor	-
Q	Average throughput	bbl/yr
H_O	Effective depth	feet
A	Exposed surface area	$feet^2$
Site (Environmental):		
V	Average wind speed	mph
ΔT	Average ambient diurnal temperature change	°F
θ	Average ambient temperature	°C

$$P^* = \frac{(P/P_A)}{[1 + (1-P/P_A)^{0.5}]^2}$$

** where P_A = average atmospheric pressure = 14.7 psia

3. Design and Operating Practices

For a tank with fixed capacity and throughput, design considerations to control air emissions include surface area minimization and inflow/outflow pipe locations. The choice of a fixed roof tank, external or internal roof tanks, and other types of tanks are also viable design alternatives. An operational change that could decrease emissions is the temperature of the influent. These practices are discussed in Surface Impoundments.

4. In-Situ Controls

Technologies applied at a tank can be used to change one or more of the parameters that affect emission rates from the surface of an open tank. The in-situ controls described below are: fixed roof, floating roof, rafts, and floating spheres.

4.1 Fixed Roofs

It is commonly accepted that fixed roofs over open tanks reduce emissions. Fixed roofs with a pressure/vacuum vent only release vapors when the internal pressure is exceeded. Fixed roofs are generally dome-shaped, and they are either welded or bolted onto the top of the tank wall.

Considerations in designing a fixed roof for an open tank include:

- o The pressure vacuum settings of the breather valve in a tank is determined by the structural strength of the tank for safety, and the maintenance of a vapor concentration below the lower explosive limit.

- o As shown in the equations above, the choice of paint on a tank is an effective means of reducing emissions, although the factor is more important for the fixed-roof tank than the floating roof tank. A highly reflective paint reduces the temperature of the tank and the liquid stored in the tank.

- o Roof material must be compatible with waste components.

Another kind of roof which may or may not be fixed is the aluminum dome. Information for this technology was obtained from Temcor in Torrance, California (1983). The material used in the construction of aluminum domes are aluminum alloys. The dome is formed using aluminum struts to form a triangular space truss. This is then covered with triangular panels. The dome does not require any columns for vertical support. Individual domes can be constructed alongside tanks and lifted into place. Hundreds of aluminum domes have been installed all over the country. Aluminum domes have been used to cover petroleum storage tanks, bulk storage areas, wastewater treatment tanks, water and other liquid storage tanks. In wastewater treatment, for example, hydrogen sulfide or other gases from treatment can be collected and treated. The dome also provides insulation to increase process efficiency.

Each aluminum done is designed for the purpose at hand. An important consideration in its use as a storage/treatment tank cover is the structural strength of the tank wall because it is the main support for the dome. The waste in the tank has to be compatible with aluminum.

Vapor losses due to wind venturi action are eliminated because there are no seals used as in the case of a floating roof. There are no floating roof weather problems. The aluminum dome is maintenance free (according to Temcor) and aluminum is very resistant to corrosion. Since there are no columns necessary in the design of an aluminum dome, there are few appurtenances. According to Temcor, the cost of an aluminum dome is competitive with a steel cover. Expensive downtime is eliminated because individual domes can be constructed separately and then lifted into place.

4.2 Floating Roofs

An excellent description of floating roofs and the types of seals available with floating roofs is given in U.S. EPA (1980). There are basically two kinds of floating roofs, external and internal floating roofs. Internal floating roofs are again divided into two types: contact where the roof floats on the liquid surface and non-contact when the roof is supported on pontoons several inches above the liquid surface.

Floating roofs are by far the most commonly used method of hydrocarbon loss control in the petroleum industry. They are generally considered inherently effective in reducing emission losses. Most vendors claim reductions of around 95 percent over fixed roofs (U.S. EPA, 1976). In the internal floating roof, the fixed roof is vented to allow sufficient air into the tank to maintain a vapor concentration below the lower explosive limit. All internal floating roofs are designed to be retrofitted into existing fixed roof tanks. Seals for floating roofs are normally sold separately from the roof and are not necessarily dependent on the roof design (U.S. EPA, 1976).

According to Jonker et al (1977), the type of seals used is important in determining emission losses from tanks. Maintenance of seals was also found to be important in reducing emissions. Secondary seals were determined to be effective in reducing emissions in this study. Gaps between tank walls and seals of greater than 1/8 inches were also found to be unavoidable for the vast majority of tanks. As expected, these authors concluded that the amount of liquid exposed to a gap, the access of wind through the gap and to the vapor above the liquid, and the length of path for the vapors to reach the atmosphere were important parameters in controlling air emissions.

Runchal (1978) used a cyclone fence on the tank top to modify the aerodynamics above the roof of an external floating roof. He found significant reductions in the pressure differences on the two sides of the roof. Substantial impact on windflow was therefore achieved by the fence and wind-induced emissions were also probably reduced significantly as a result although emissions were not measured. Significant reductions were also obtained when the floating roof operated at a greater depth from the top of the tank (greater freeboard). These tests show the importance of the wind speed and flow in determining emissions from external floating roofs and are considerations in the design of a floating roof tank.

Other considerations include:

- Stability of the floating roof under stresses of water and snow. A pan floater is less stable than a pontoon roof (Air Pollution Control Association, 1971). A covered floating roof does not have this problem.
- Insulation of the roof can reduce temperatures in the tank. In a floating roof tank, a double-deck roof is not only more stable but has insulating qualities as well (Air Pollution Control Association, 1971).
- Roof material and seals must be compatible with waste components.
- Modifications to the tank may be necessary. Tank wall deformations and obstructions may have to be corrected so that seals will conform to the wall.

4.3 Rafts

Please see discussion in Surface Impoundments.

4.4 Floating Spheres

Please see discussion in Surface Impoundments.

5. Post-Treatment

As discussed in post-treatment in surface impoundments, collection and post-treatment requires collection of emissions by means of a cover and a vent, and treatment units(s) at the vent. In the case of tanks, the collection system may consist of a fixed roof or an aluminum dome with a vent, and post-treatment with a variety of treatment technologies. Descriptions of two approaches, carbon adsorption and afterburners are given in the chapter on Surface Impoundments.

A post-treatment system has been installed at a facility owned by Waste Conversion in Hatfield, Pennsylvania. This facility treats wastes including acids, caustics, sewer sludges, coolants, food processing wastes in about 25 tanks. All of these are hooked up to scrubbers. The first scrubber was installed 4 years ago, and there have been numerous additions since. The post-treatment system includes carbon adsorption (sent to another company for regeneration), wet scrubbers with sodium hypochlorite and caustic soda, and precipitators. In this facility, there is some in-situ control as well, in the addition of activated carbon to treatment solutions themselves to adsorb volatiles before emission. The whole system is large, e.g., the carbon adsorption consists of 5 carbon drums 12 feet in diameter and 9 feet high each. The primary purpose of all the controls is the reduction of odors. Otherwise, the operators of this facility believe that they do meet point source air standards with controls. So far, the system costs around $500,000 (Waste Conversion, Personal Communication, July, 1984).

D. Effectiveness of Tank Controls

1. Methodology

1.1 Selection of Parameter Values

To evaluate the effectiveness of controls in reducing emissions from tanks, waste, tank and site (environmental) parameters necessary for quantifying emissions were defined. These parameters were shown in Table IV-2. Parameters required to calculate emissions from open tanks were the same as those used in surface impoundments except for wind speed at the surface of the liquid. This was varied because efficiencies from the baseline of using controls are very sensitive to the surface wind speed.

From various sources of data, GCA (1983) compiled typical ranges of values for input parameters used in relationships for calculating emission losses from tanks.

One tank size was chosen from these data as a representative tank. Other average or representative values were chosen for all parameters within reasonable expectations of tank design and operation. Some economies of scale are expected for larger sizes. The general cost-effectiveness relationships developed below for the single representative case are expected to hold for larger sizes.

1.2 Calculation of Mass Transfer Coefficients and Emissions

The storage tank was selected to represent the tanks in use. Treatment tanks were not considered as different because technologies to control emissions would be similarly effective in treatment and storage tanks, unless the treatment tank was aerated in which case floating roofs, rafts and floating spheres would not be viable as control technologies. However, for each technology that is applicable to both types of tanks, the relative efficiencies and cost-effectiveness would be equivalent. It was also assumed that emissions were liquid-phase controlled.

The relationships for calculating mass transfer coefficients and emissions losses were shown in Table IV-1. Total emissions from open tanks were calculated as in surface impoundments. The floating roof tank chosen for comparison is the external floating roof tank. Emissions using rafts and spheres were calculated as 10 percent of baseline plus losses due to clingage during withdrawal using L_w for floating roof tanks.

1.3 Emission Reduction and Efficiencies of Controls

The open tank was used as the basis of comparison for all the control technologies, i.e., it was considered the tank without controls.

The reduction in emission rates is defined by:

$$R = Q_1 - Q_2 .$$

where the subscripts 1 and 2 refer to tanks without controls and with controls respectively.

The efficiency (E) is defined by:

$$E = 100 (Q_1 - Q_2)/Q_1$$

The reduction in emission rates depends on the baseline selected in terms of surface wind speed in the open tank. The efficiencies of controls are extremely sensitive to surface wind speed. Curves of efficiencies of the controls with varying surface wind speeds will be shown.

1.4 Cost-Effectiveness of Controls

The in-situ controls for emissions reductions were compared using the cost of each percent of reduction efficiency per square feet of surface area ($/percent-$ft^2$). Curves were developed to show cost-effectiveness with varying surface wind speed based on the relationships in Table IV-1. Pretreatment, in-situ controls, and post-treatment were compared by considering the curves of cost per pound removed (reduced) versus pounds per year removed (reduced). Similar curves were generated for cost per pound removed (reduced) versus throughput in pounds per year. As in the discussion on surface impoundments the curves are:

In-Situ $$y = \frac{A}{R} \qquad (\$/\text{lb-reduced})$$

$$y = A/ET \qquad (\$/\text{lb-reduced})$$

Post-Treatment $$y = \frac{F}{R} + p \quad (\$/\text{lb-reduced})$$

$$y = \frac{F}{ET} + p \quad (\$/\text{lb-removed})$$

where: A = annual cost of in-situ control (\$/year)
R = reductions (removal) (lb/year)
E = efficiency of control
T = throughput (lb/year)
F = cost of collection per year (\$/year)
p = cost per pound of post-treatment (\$/lb)

We compared in-situ, post-treatment and pretreatment using different pretreatment costs as taken from Spivey et al (1984). In-situ costs were obtained from vendors for the tank size in this study. Post-treatment costs were obtained from EPA (1982).

2. Parameters

The values for the parameters used in quantifying emissions are shown in Table IV-3. A tank 45.75 ft in diameter and 40 feet tall with a capacity of 11,700 bbl was taken as a representative tank. The turnover rate was 70 turnovers per year. Primary and secondary seals were assumed to be used in the floating roof and that they were in good condition. The waste parameter (P) was chosen as a representative value for wastes stored in tanks.

3. Emissions

Emissions were calculated using a mole fraction of 1 for the volatile components in the impoundment. Emissions from open tanks were calculated for wind speeds at the liquid surface varying from 10^{-5} ft/sec to 10^{-2} ft/sec.

4. Emissions Reduction and Efficiencies

In-Situ

Emissions reductions and efficiencies of each of the in-situ controls are shown in Table IV-4. Curves of efficiencies of controls with varying surface wind speeds are shown in Figure IV-1. Figure IV-1 shows that at very low surface wind speeds, rafts and floating spheres are more efficient than fixed roofs. External floating roofs, the most efficient controls, are much more efficient than fixed roofs at low surface wind speeds but at higher surface wind speeds, the efficiencies of both approach each other. At higher surface wind speeds, rafts and spheres become less efficient than fixed roofs.

TABLE IV-3

PARAMETER VALUES FOR TANKS**

PARAMETER	VALUE	UNITS
Waste:		
M	100.08	lb/lb-mol
P	2.5	psia
K_C	1.0	-
P^*	0.0466	-
C_L	0.3	bbl/1000 ft^2
W_L	9	lb/gallon
Tank:		
D	45.75	feet
H	10	feet
F_P	1.3	-
C	1.0	-
K_N	0.6	-
K_S	0.7	-
N	0.4	-
E_F	0.75	-
Q	8.2×10^5	bbl/year
H_o	30	feet
A	1643.9	feet
Site (Environmental):		
V	10	mph
ΔT	15	°F
θ	25	°C

** Assume tank is 40 feet tall capacity = 11,700 bbl, and turnovers per year = 70. Primary and secondary seals, both the good condition.

Source: Arthur D. Little, Inc.

TABLE IV-4

EMISSIONS REDUCTIONS AND EFFICIENCIES OF CONTROLS IN TANKS

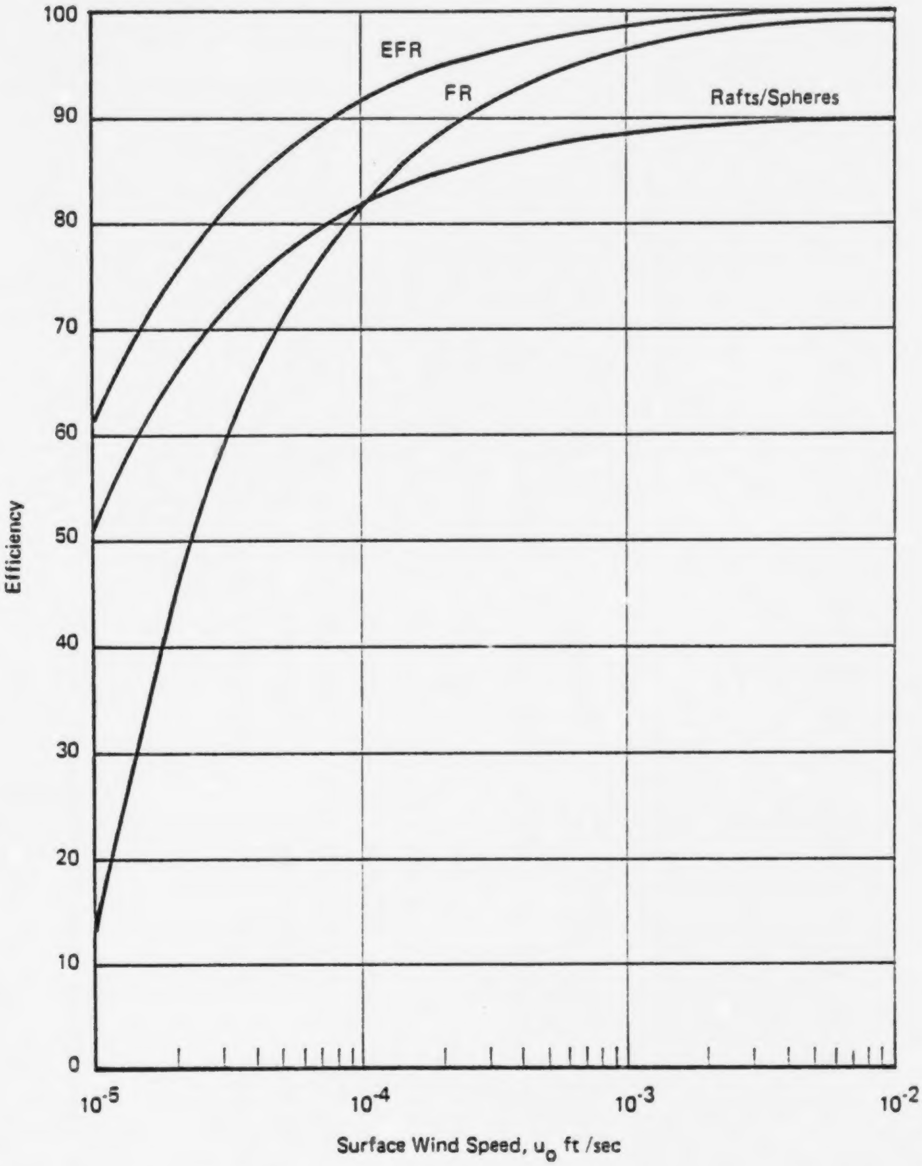
Surface Wind Speed (U_o/ft/sec)	Reductions (lb/yr)[*]			Efficiency		
	FR[**]	EFR[***]	Rafts/ Spheres	FR	EFR	Rafts/ Spheres
10^{-5}	16,107	72,603	61,032	13.6	61.3	51.5
2×10^{-5}	86,431	142,656	124,080	45.8	75.6	65.8
10^{-4}	451,944	508,440	453,286	81.5	91.7	81.8
2×10^{-4}	779,609	836,105	748,184	88.4	94.8	84.8
10^{-3}	2,490,508	2,547,004	2,287,993	96.1	98.2	88.2
10^{-2}	12,025,586	12,082,082	10,869,563	99.2	99.6	89.6

[*] Using unit mole fraction of volatile component

[**] FR - Fixed Roof

[***] EFR - External Floating Roof

Source: Arthur D. Little, Inc.



FR = Fixed Roof
EFR = External Floating Roof

Source: Arthur D. Little, Inc., 1984

FIGURE IV-1 EFFICIENCIES OF IN-SITU CONTROLS FOR TANKS

Post-Treatment

Two post-treatment systems were chosen for comparison: carbon adsorption with no regeneration, and afterburning. The rate of emissions is affected by the collection system and the pressure through the post-treatment unit(s). Carbon adsorption was assumed to work at an efficiency of 95% and afterburning at 98%.

5. Costs

Pretreatment

Pretreatment costs taken from Spivey et al. (1984) were in the order of $1.00 per pound of volatiles removed ($2,200/Mg) and represented the range of most pretreatment technologies within a factor of 2.

In-Situ Controls

Costs for fixed and external floating roofs were obtained from a vendor, the Chicago Bridge and Iron Company (Personal Communications, July 1984). Costs for aluminum domes were obtained from Temcor, Torrance, CA (Personal Communications, October 1983). The material costs for rafts and spheres were those used in surface impoundments.

In order to estimate installation costs for roofs, the location was assumed to be the Midwest. Costs for roofs were derived by taking the difference in a new tank with a roof and a tank without a roof. According to the vendor, the costs estimated independently would be within the same magnitude of error (± 10 percent) as the figures derived by taking the difference.

Installation costs were included in the cost estimates for roofs. The cost for aluminum domes includes all costs. Rafts and floating spheres have very low installation and maintenance costs. These costs are not included in the estimates given in Table IV-5. Disposal costs for rafts and spheres were not included.

Roofs have a long lifetime (over 25 years). It was assumed that rafts last 1 year and that floating spheres had a lifetime of 10 years. Costs for roofs and spheres were annualized at 10 percent for 10 years. The cost per year is around 16 percent of the total cost after annualization. Total costs and annualized costs are shown in Table IV-5.

Post-Treatment

Costs for post-treatment consists of the costs for collection and treatment. The collection system is either the fixed roof or the aluminum dome. These costs were estimated for in-situ controls and shown in Table IV-5. Treatment costs are variable costs dependent on the total emissions treated. These costs for carbon adsorption

TABLE IV-5

TOTAL COSTS AND ANNUALIZED COSTS FOR CONTROLS (Summer 1984 Dollars)

Tanks[1]	Total ($)
Open top with wind girder	95,000
With column supported cone roof	115,000
With double deck external floating roof incl. primary and secondary seals	215,000

In-Situ	Total ($)	Annualized ($/yr)[2]
Column supported cone roof	20,000	3,200
Aluminum dome[3]	16,000 - 25,000	2,600 - 3,900
Double deck external floating roof incl. primary and secondary seals	120,000	19,000
Rafts	130 - 210	130 - 210
Floating spheres	10,800 - 14,300	1,700 - 2,300
Post-Treatment		
Collection (excl. treatment)	16,000 - 25,000	2,600 - 3,900

1. For tanks 45.75 feet in diameter, 40 feet high. Including erection and installation, assuming Midwest location. Not including land or foundations, piping, valves, and other appurtenances. Source: Chicago Bridge and Iron Co., Boston, MA 1984.
2. Annualized for roofs, domes, and spheres at 10% in 10 years.
3. Source: Temcor, Torrance, CA. 1983. Estimated at $10-15 per ft^2 with installation.

without regeneration and afterburning were estimated in the discussion on surface impoundments and were around \$45 and \$16 per pound, respectively (\$100,000/Mg and \$35,000/Mg). If carbon regeneration and catalytic afterburner systems were included, treatment costs would be between \$5-10 per pound (\$11,000-\$22,000/Mg).

6. Cost-Effectiveness of Controls

Table IV-6 and Figure IV-2 express the cost-effectiveness of in-situ controls in terms of the cost per percent of reductions per square foot of tank for surface wind speeds ranging from 10^{-5} to 10^{-2} ft/sec. Since aluminum domes and column supported cone roofs are similar, only one curve is shown for these two controls. Only the average for rafts and spheres are shown.

Rafts appear to be the most cost-effective of all the in-situ controls. External floating roofs are the least cost-effective, being much more expensive than the other controls. When the tank is operated in a very quiescent situation (e.g., very high freeboard or in a site with extremely low wind speed), external floating roofs and fixed roofs (or aluminum domes) become more comparable. Under these conditions, rafts and floating spheres are more cost effective than any of the roofs. As wind speed increases (e.g., if the tank is consistently operating at very low freeboards or if wind speed is high in the site of operation), fixed roofs and aluminum domes become more comparable with rafts and spheres.

Figures IV-3 and IV-4 show the hyperbolic functions relating cost per pound of emissions reduced or removed to the throughput of volatiles per year and the total pounds of volatiles removed per year respectively. The horizontal lines represent the pretreatment cost per pound of volatiles removed. The hyperbolic curves are at a constant annual cost of in-situ controls and for three levels of post-treatment costs.

Figure IV-3 incorporates the efficiency of each control technology by considering the throughput of volatiles. An efficiency of 90 percent was used for external floating roofs, and a corresponding efficiency of around 76 percent and 80 percent were used for fixed roof tanks and rafts and spheres respectively. The most cost effective of the controls is rafts except where throughput is very small (below 200 lb/yr at pretreatment cost of \$1/lb (\$2,200/Mg). At the bottom left of the figure where the horizontal pretreatment lines are below the hyperbolic curves, pretreatment is more cost-effective. Above a throughput of around 5×10^3 lb/yr, spheres and fixed roofs are more cost-effective than pretreatment at around \$1/lb (\$2,200/Mg). Spheres are more cost-effective than fixed roofs. The use of post-treatment is expensive compared to all the other controls except when throughput is very low (around less than 4×10^2 lb/yr for carbon adsorption at \$45/lb (\$100,000/Mg) and around 10^3 lb/yr for afterburning at \$16/lb (\$35,000/Mg). Gen[illegible]ly, post-treatment becomes less cost-effective as throughput increases.

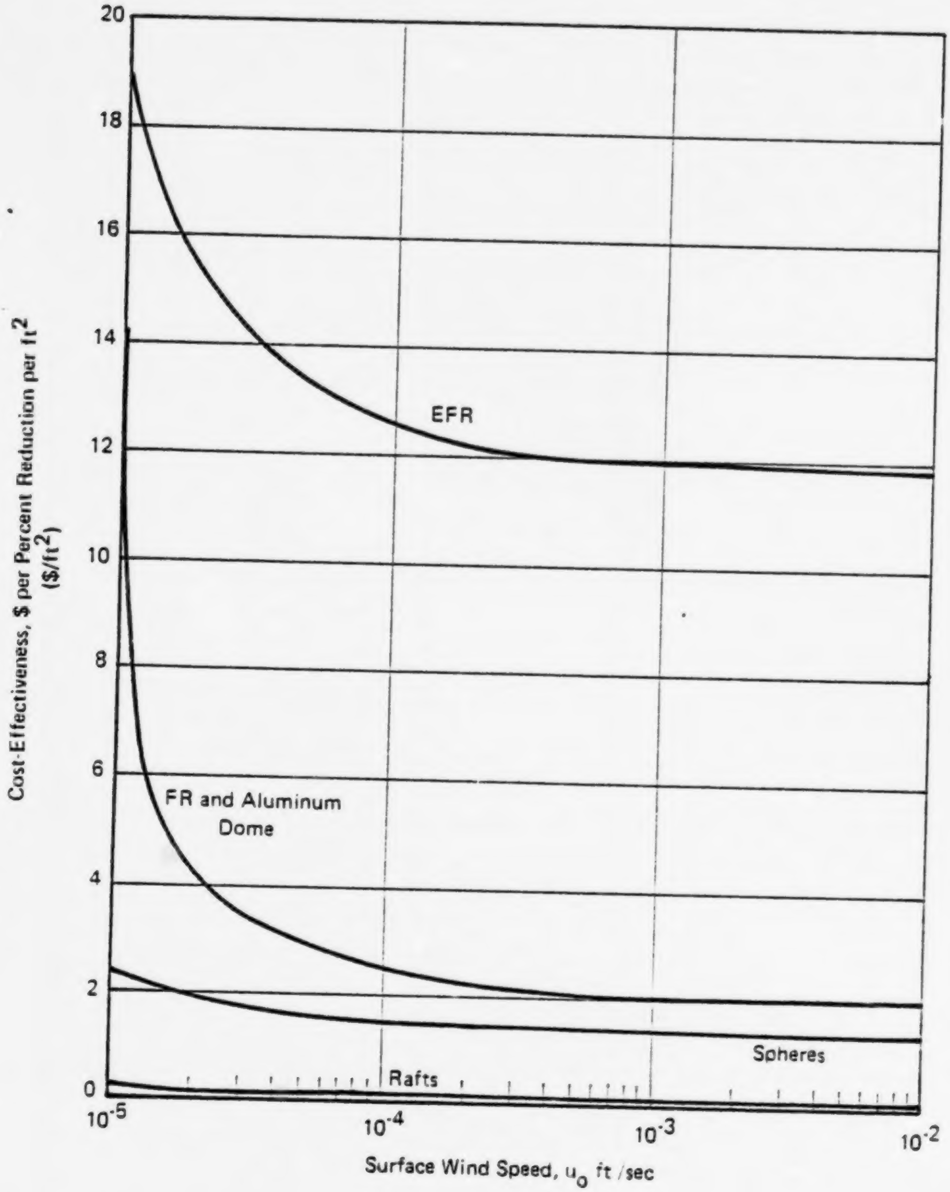
TABLE IV-6

COMPARATIVE COST-EFFECTIVENESS FOR TANK IN-SITU CONTROLS

Surface Wind Speed (ft/sec)	Cost-Effectiveness* Column Supported Cone Roof	Aluminum Dome	Double Deck Ext. Floating Roof	Rafts	Spheres
10^{-5}	14.2	11.7 - 17.5	18.9	0.2 - 0.3	2.0 - 2.7
2×10^{-5}	4.2	3.5 - 5.2	15.3	0.1 - 0.2	1.6 - 2.1
10^{-4}	2.4	2.0 - 2.9	12.6	0.1 - 0.2	1.3 - 1.7
2×10^{-4}	2.2	1.8 - 2.7	12.2	0.1 - 0.2	1.2 - 1.6
10^{-3}	2.0	1.7 - 2.5	11.8	0.1	1.2 - 1.6
10^{-2}	2.0	1.6 - 2.4	11.6	0.1	1.2 - 1.5

*Cost-Effectiveness is expressed in $\$ \times 10^{-2}$ per percent emissions reduction per square foot. Multiply values in the table by 100 to get values in dollars.

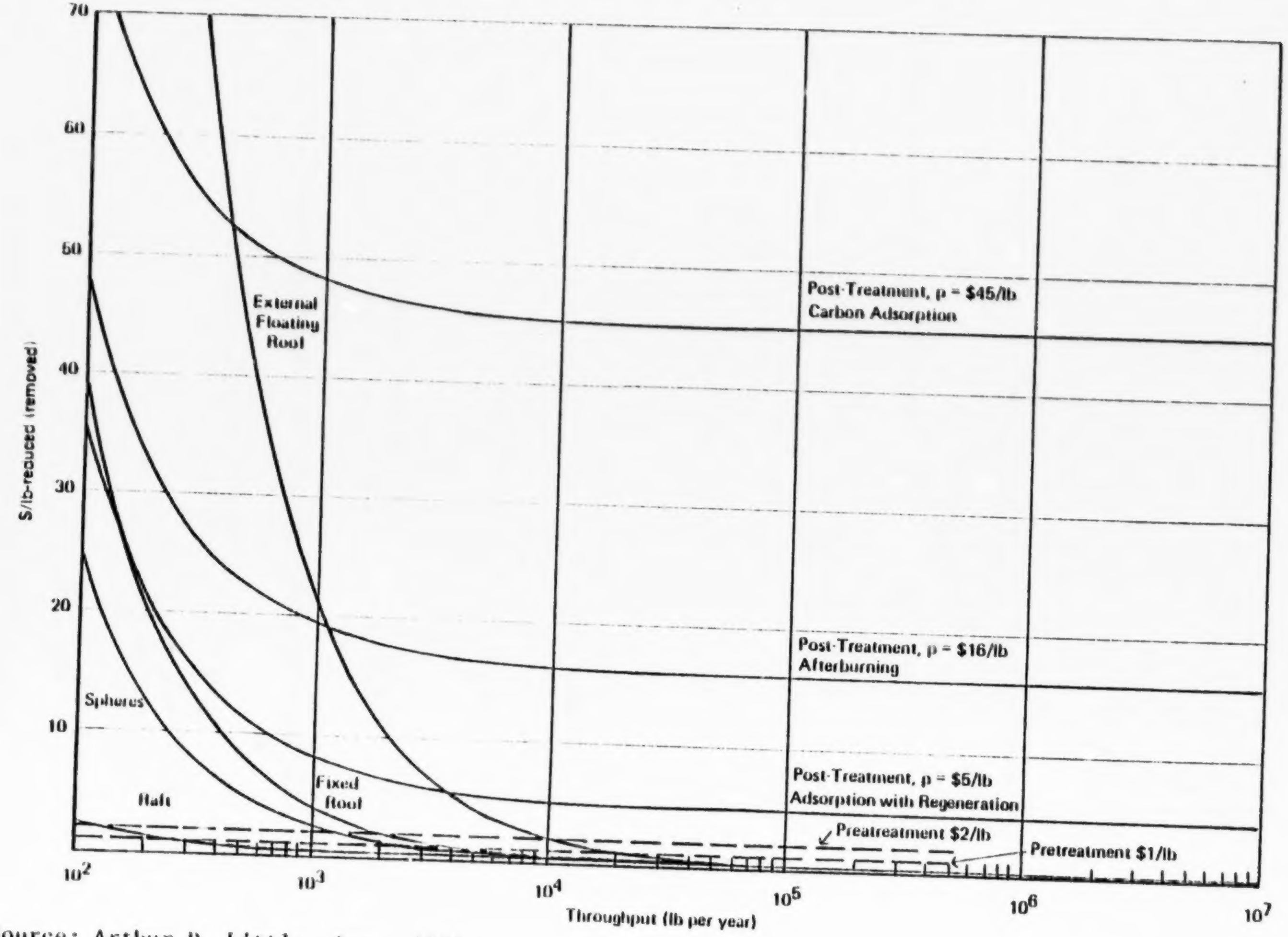
Source: Arthur D. Little, Inc.



FR = Fixed Roof
EFR = External Floating Roof

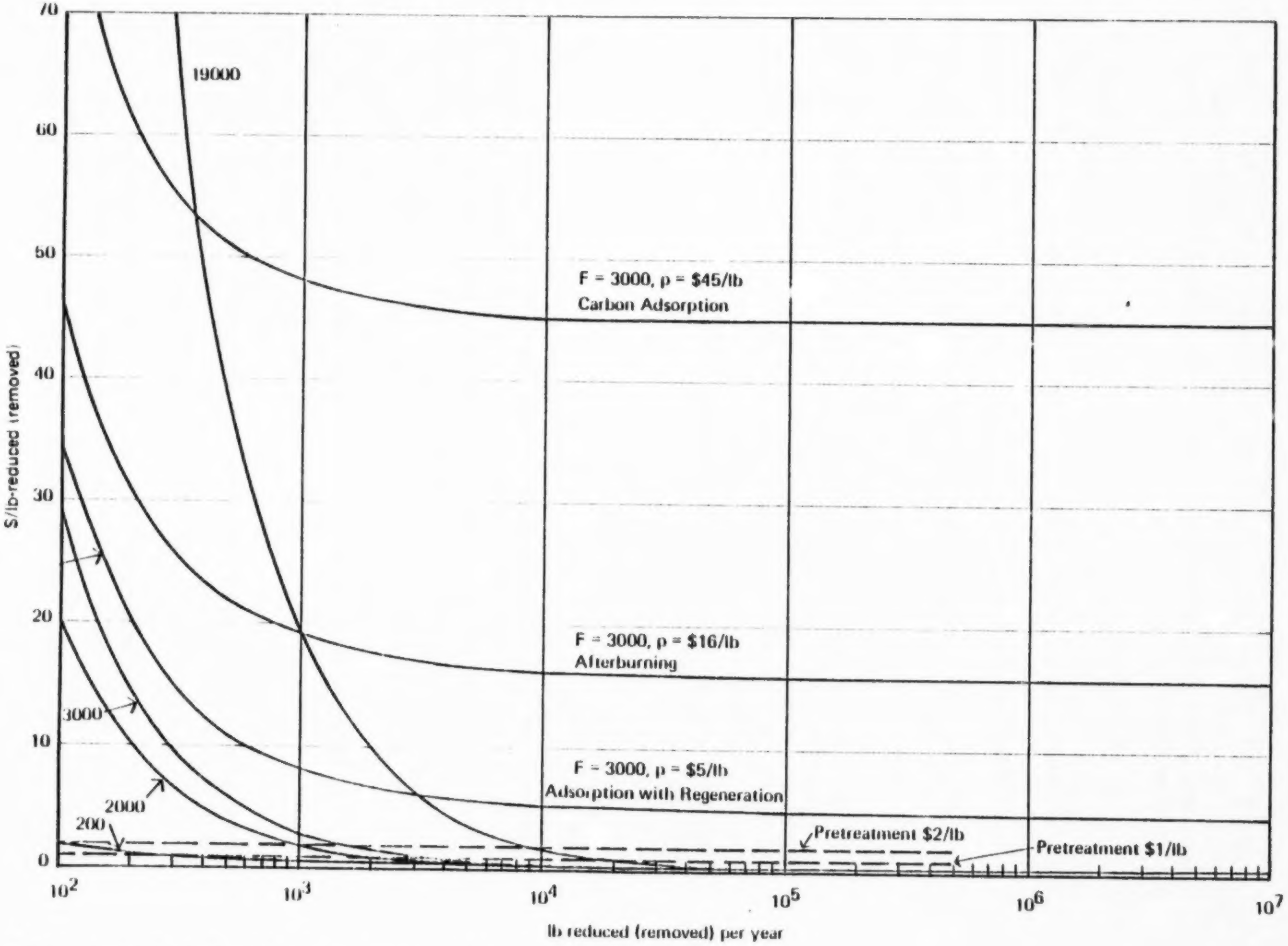
Source: Arthur D. Little, Inc., 1984

FIGURE IV-2 COMPARATIVE COST-EFFECTIVENESS OF IN-SITU CONTROLS FOR TANKS



Source: Arthur D. Little, Inc., 1984

FIGURE IV-3 COST EFFECTIVENESS OF CONTROLS ON TANKS VERSUS THROUGHPUT



Source: Arthur D. Little, Inc., 1984

FIGURE IV-4 COST-EFFECTIVENESS OF CONTROLS ON TANKS VERSUS REDUCTION

If the price of post-treatment can be reduced, it may become more cost effective than external floating roofs at throughputs of less than around 10^3 lb/yr (e.g., if post-treatment costs \$5/lb (\$11,000/Mg) with carbon regeneration). Under low post-treatment costs, post-treatment may even become more cost-effective than fixed roofs at low throughputs.

In the analysis, the efficiencies and the cost-effectiveness of roofs are probably underestimated with respect to spheres and rafts. Fixed roofs are likely to be very comparable to using spheres. However, because of the low cost of rafts, they are still the most cost-effective.

Figure IV-4 shows the cost-effectiveness versus the pounds per year reduced or removed per year. Each of the hyperbolic curves represents an annual cost. In-situ controls are favored to pretreatment as the pounds per year is increased. If an in-situ control has an annual cost of \$3,000/yr (corresponding to fixed roof or aluminum dome), a reduction rate of 3,000 lbs/yr is the trade-off point at which the in-situ control becomes more cost-effective than pretreatment at the cost of \$1/lb (\$2,200/Mg). If pretreatment cost was increased to \$2.00 per pound (\$4,400/Mg), a rate of reduction (removal) of greater than 1500 lbs/yr would favor the in-situ control costing \$3,000 a year.

E. Summary

Roofs are well-used, proven emission control technologies from petroleum storage facilities. Floating spheres, and to a much lesser degree, rafts have been used in treatment tanks in the chemical industry for emissions control. Pretreatment and post-treatment are taken from proven, similar applications and are easily applicable in the case of tanks. Waste Conversion in Hatfield, PA, is a good example where post-treatment has been used effectively to control emissions from treatment tanks. As an example of a commercially available product, Calgon Corporation offers Ventsorb, a catalogue item. Ventsorb is a 55-gallon drum containing activated carbon specifically developed to be used at vents in tanks, landfills, and process applications. Each unit costs between \$535-\$635, and is normally disposed of after usage. The units can also be taken apart and the carbon replaced. Replacement carbon costs around \$300 per unit. (Calgon Corporation, Personal Communication, September 1984).

Certain technologies may be applicable in storage tanks but not in treatment tanks. Floating roofs are generally not applicable in treatment tanks. Spheres and rafts are not applicable in aerated tanks. Fixed roofs, pretreatment and post-treatment are applicable to both kinds of tanks.

If an in-situ control that reduces emissions by decreasing volatilization (e.g., spheres, rafts, fixed roofs) is used in a treatment tank, the absolute removal can be increased by the additional time volatiles are retained in the tank, and therefore, the additional amount of treatment obtained. This was not included in our analysis. The hyperbolic curve in this case would be shifted to the left and the in-situ control will be more cost-effective at a lower trade-off point.

In a similar way, in-situ controls which reduce emissions by reducing volatilization when used in storage tanks containing wastes in transition before treatment increase the absolute removal by increasing the volume treated. In treatment tanks which are at the final stage of the process, post-treatment which removes emissions from these tanks may be the only means of absolute removal in some cases, e.g., in aerated tanks or in tanks containing waste before disposal.

The trade-off point at which a control is equally cost-effective with pretreatment is very sensitive to pretreatment costs as in the case of surface impoundments. For a small change in pretreatment cost, the trade-off point will shift relatively far to the left (with greater pretreatment cost) or to the right (with smaller pretreatment cost).

In practice, the choice of one control over another will probably not be based on cost-effectiveness as the only evaluation criterion. The use of the tank, its size, the downtime required for retrofitting, the structural strength of its walls, and the amount of structural changes that have to be made will probably be important determining factors as well. As an example, floating roofs are normally used on large tanks because they are very expensive and significant economies of scale exist. In situations where the tank walls are deformed due to age or other reasons, they cannot be easily retrofitted into a tank without a large amount of extra expenses. In a case of small tanks and particularly tanks with wall deformities, spheres and rafts would be more viable, maintenance-free solution with no expenses needed in retrofitting. In a tank with insufficient wall strength, aluminum domes with no columnar supports will not be a good alternative.

The design and operation of a tank may present opportunities of emissions reductions. In a new tank where retrofitting and downtime do not present problems, installation of roofs and other major changes in design (e.g., pressure tanks or variable pressure tanks) may be viable solutions.

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V. LANDFILLS

A. Landfill Description

A landfill is a waste disposal facility where wastes are placed in or on the land for custodial safekeeping. A variety of control techniques is required by regulation as well as good operating practices to isolate the wastes from the environment. A typical landfill facility contains three types of areas: an unused portion for future operations, a currently operating portion or set of cells, and one or more closed cells.

Operations consist of placing wastes arriving in various modes into the landfill in a manner to obtain maximum utilization of the volumetric capacity and minimize exposure to workers and ultimately to the environment. Wastes arrive in containers, or as bulk solids or liquids. Containers are placed directly in the landfill, generally in regular patterns. Bulk solids are deposited directly in the landfill and are distributed over the operating area by use of earth-moving equipment. Bulk liquids are mixed with solidifying agents prior to being placed in the landfill. After being mixed with these agents, liquids are handled essentially in the same manner as bulk solids.

At the end of each operating day or at less frequent intervals, a soil cover is placed over the wastes deposited during that day. The soil cover generally consists of from 6 to 12 inches of soil, fly ash, or other aggregates capable of being spread, compacted and supporting subsequent layers (lifts) of wastes and covers.

The area of an operating cell ranges from a few tenths of an acre at many currently operating sites to as much as several acres at a few large operations.

Eventually the wastes placed in a working cell together with the daily cover materials will reach the cell's capacity. When this occurs, operations at that cell cease and it is closed permanently. Closure consists mainly of placing a permanent cover over the cell followed by monitoring the integrity of the system for a period of many years. The cover may consist of several layers, the uppermost of which is vegetated to prevent erosion and in some cases to permit use of the land surface following closure.

Long-term degradative processes continue in the waste mass after the cell has been closed. Infiltration of surface water can generate leachate. Containers will generally deteriorate and may release their contents after long exposure to mechanical stresses and the normally corrosive environment in a landfill. The waste materials may be degraded by chemical processes such as hydrolysis or by anaerobic bacterial decay. The next section describes potential sources of emissions to the atmosphere associated with the several major stages of operation at a typical landfill.

B. Emission Sources and Models

1. General

During operations emissions may arise from activities at the uncovered area (or operating face), and through the area with the daily (or temporary) cover. In addition, volatile compounds can permeate the final (permanent) cover over closed sections of the landfill. The rate of emission depends, generally, on the wastes and the form in which the wastes are deposited, ambient conditions and operating practices at the facility.

At the operating face, waste can be deposited as bulk solids, containerized wastes, or bulk liquids. Containers are assumed to be leak tight so that no emissions are generated. If the containers lose integrity at some later date, then the volatile constituents can utltimately permeate through the entire waste mass and diffuse through the cover into the air. Volatile constituents in bulk solids diffuse to the surface and into the atmosphere. The rates are generally quite low as many volatile compounds become absorbed on the solid surface and exhibit low vapor pressure.

Bulk liquids may be deposited in landfills only after they have been solidified with a bulking agent. In some operations bulking is carried out by adding liquids directly to the bulking agent near the operating face and then placing the mix in the landfill. It is possible to have pools of liquid present for short periods, although good practice would avoid this situation. In this case emissions would be similar to those at a surface impoundment with a floating organic layer or a land treatment site immediately following a surface application of wastes. Since this situation (pooled liquids) should be avoided for many reasons, including safety, good operating practice, etc., it will not be considered further in this analysis.

The mix of liquid and bulking agent may be exposed for significant times at the operating face. During this time, emissions occur by mechanisms related to those at land treatment facilities where wastes are placed on and tilled into soil surfaces.

Emission through daily or permanent covers results from diffusion of vapors arising from the bulk of the wastes upward and through the cover. The process occurs in stages. Vapors from the lowermost lifts (stages in the filling sequence) diffuse through the first cover into the second lift and so on until the vapors reach the uppermost lift. In active, operating cells the uppermost temporary cover will be the same as all the others; in the closed portion the uppermost cover will be the permanent seal and generally will be less permeable than the daily covers. The rate of loss will be controlled by the uppermost cover, whether it is final or temporary, as vapors will gradually equilibrate among the various lifts.

In addition to the basic diffusion mechanisms, emission through the covers are also influenced by several other processes. In hazardous waste landfills with codisposed, mixed biodegradable wastes, methane can be generated through anaerobic decay. The methane will build up and gradually flow upwards (and laterally as well) carrying volatile compounds with it. Barometric pumping, due to fluctuations in ambient pressure, can also increase flow relative to purely diffusive mechanisms.

Lateral diffusion will occur as well as vertical diffusion. Vapors diffusing sideways out of the fill may then turn and diffuse to the surface. The requirement for liners at the sides and bottom of hazardous waste landfills will minimize emission via this mechanism.

Emissions may also arise from the leachate which is generated within the landfill and is removed through the leachate control system. Leachate may contain free, immiscible organic contaminants and dissolved volatile species. Leachate may be exposed to the atmosphere in sumps or in tanks where the leachate is stored pending treatment and disposal. Controls for leachate-based emissions are not considered explicitly in this study. Leachate is essentially a new liquid hazardous waste. Emission controls depend on the types of TSDF used to manage it.

2. Emission Models

Emission models are developed below to illustrate how emissions depend on various controllable parameters and to provide a means for quantitative analysis. The models cover only the parts of the emission processes that are most significant. Models are given for diffusion through covers and for volatilization from bulk solids and solidified bulk liquids.

Covers

The basic steady-state relationship for diffusion through covers is:

$$Q = \frac{A\, D_{eff}(C_i - C_o)}{t_c}$$

where:

Q = volatilization rate (lb/hr)

A = area of cover (ft^2)

D_{eff} = effective diffusivity (ft^2/hr)

C_i, C_o = concentration of vapor on underside and top of cover, respectively (lb/ft^3)

t_c = thickness of cover (ft)

For the top cover, the concentration in the atmosphere can generally be neglected relative to the concentration below the cover. Effective diffusivity expresses the diffusive behavior of a single compound through the pores of the cover for soils or through the fabric of a synthetic cover. Of several equations available for soil-type covers, Farmer's (1978) equation appears most appropriate in terms of the objectives of this analysis. It is relatively simple but indicates how diffusion relates to soil properties. Farmer's equation is:

$$D_{eff} = D_{air} \frac{(\varepsilon_a)^{10/3}}{(\varepsilon_t)^2}$$

where: D_{air} = diffusivity of compound in air (ft^2/hr)
ε_a = porosity of air-filled pores
ε_t = total porosity

Further, porosity can be related to the density to which the soil has been compacted as:

$$\varepsilon_t = 1 - {}^{\beta}/_{\rho_s}$$

where: β = soil bulk density (lb/ft^3
ρ_s = particle density (lb/ft^3)

If the soil is completely dry, then total porosity and air-filled porosity are the same and the effective diffusity becomes the normal diffusivity in air. If the soil is wet, part of the pore volume becomes filled by water. In this case, the air-filled porosity becomes:

$$\varepsilon_a = \varepsilon_t - \frac{\omega}{\rho_w}$$

where: ω = gravimetric soil water content, lb/ft^3
ρ_w = water density (lb/ft^3)

For synthetic covers, the basic form of the mass flow relationship is similar.

$$Q = \frac{A\, D_m\, C}{t_m}$$

where: A = area of cover (ft^2)
D_m = permeation rate of a given diffusing compound through synthetic cover material (ft^2/hr)
C = concentration of diffusing vapor at the top of the landfill (lb/ft^3)
t_m = thickness of synthetic cover (ft)

The concentration term in the basic equation represents an equilibrium either between vapor and a volatile organic adsorbed on a solid surface or between vapor and a free liquid in the interstices of the wastes or soil. In the first case, adsorption, the particular form of the relationship depends on many factors; chemical structure, quantity, temperature, etc. One common form of equation, the Freundlich equation relates vapor concentration to quantity adsorbed as (Weiser, 1949):

$$c = k\, x^n$$

where: c = vapor concentration (lb/ft^3)
k = empirical constant
x = mass of volatile compound absorbed per unit mass of soil
n = empirical constant

For free liquids, the vapor concentration follows the conventional relationship for solutions:

$$C = \frac{P_o\, MW}{RT}\, \gamma x$$

where: P_o = vapor pressure of pure component (atm)
MW = molecular weight of diffusing component (lb/lb-mol)
R = gas law constant (0.73 atm-ft^3/lb-mol-°F)
T = temperature (°R)
γ = activity coefficient
x = mole fraction

For dilute solutions, Henry's Law can be used as an alternate form. In all of these relationships, vapor concentration increases with increasing temperature, all other factors being equal.

Bulk liquids

The mix of free liquids and solidifying or bulking agents can be represented by the models developed for land treatment. In land treatment, also called land-farming, oily wastes are deposited on and tilled into soil surfaces. The rate of emission displays a complex time-varying relationship reflecting depletion of the volatile materials near the surface (Thibodeaux as reported in Hwang, 1982). The characteristic time for land treatment cycles is quite long relative to the period during which mixed liquids are exposed at the working face of a landfill. At landfills, bulk liquids are mixed with solidifying materials such as kiln dust, prior to deposition in the landfill. Pooled free liquids may be present, but only for short periods. The bulked liquids, in the solidified matrix, may be exposed to the atmosphere for periods ranging from hours to several days.

In this situation, it is reasonable to assume that losses occur at the exposed surface through diffusion from free liquid in the pores of the bulking agent. In this case, the mass flow equations simplify to:

$$Q = Ak_{oa} C^*$$

where: A = area of exposed face (ft^2)
k_{oa} = overall mass transfer coefficient (ft/hr)
C^* = equilibrium concentrations above free liquid (lb/ft^3)

For pure or mixed organic compounds, the overall coefficient is generally gas-film controlled and follows a law similar to those discussed in the surface impoundment chapter. The coefficient depends generally on wind speed, some characteristic dimension of the exposed surface, and diffusivity in air.

Bulk solids

Bulk solids containing adsorbed volatiles would behave very similarly to bulk liquids as described above. The equilibrium concentration (C^*) would refer to the solid surface instead of the liquid surface.

3. Controlling parameters

Covers

The factors that determine mass flow out of a soil cover are area, effective diffusivity, vapor concentration, and cover thickness. Area is generally constrained by factors considered in the overall design of a landfill. For a given volume of wastes, area can, in theory, be minimized by starting with a deeper excavation. But in practice, depth is determined primarily by hydrogeological factors (such as the water table level), geological setting, and liner and leachate collection system requirements. Thickness of both daily and final cover are matters of design and operating practice and can be set over a wide range of values depending on the objectives, including economy, infiltration prevention, emission minimization, or otherwise.

Vapor concentrations can be reduced by pretreatment, similar to the case of surface impoundments. Again, removal of the volatile compounds will reduce not only the rate of emissions, but also the total quantity released over long periods of time. Since vapor concentration is a very strong function of temperature, any means of lowering the internal temperature of the landfill would reduce volatile emissions. Diffusivity of soil cover can be modified by selection of the basic cover material, compaction, and moisture content. For synthetic covers, diffusivity can be set by choice of material and membrance thickness.

Working faces

Minimizing time of exposure and area exposed would reduce emissions. Enclosing areas in which solidification of bulk liquid is carried out would provide a means to control emissions. Ventilation and volatiles control, such as carbon adsorption, could be added. Requiring daily cover emplacement would reduce emissions at facilities that presently cover the wastes at less frequent intervals. Modifying mass transfer coefficients, as in the surface impoundment case, is not practical.

C. Controls

1. Introduction

There is a limited set of controls available for landfills compared to surface impoundments. Pretreatment results and costs are the same for all treatment and disposal modes, including landfills. Design and operating practices may reduce emissions considerably without interfering with normal operations. Discussion of permanent covers including vents is included in the design and operating practices section, although this approach could be considered as an in-situ control. With this assignment there are no so-called in-situ controls for landfills. The last group, post - treatment approaches, includes two distinct types of controls.

2. Pretreatment

Pretreatment controls are essentially the same as those described above the surface impoundments. In addition, regulations that would ban disposal of volatile organic wastes in landfills would have the same effect as pretreatment, i.e., prevent the disposal in the first place.

3. Design and Operating Practices

3.1 Handling Bulk Liquids or Solids

Emissions from bulk liquids, if permitted in landfills, can be minimized by mixing the liquids and solidification agents in closed vessels or in enclosures. Emission from closed vessels can be captured and treated with a high degree of effectiveness. Practices where liquids are poured onto the ground prior to the addition of the bulking agent should be avoided. If direct, open mixing is employed, liquids should be added to or into the solids and quickly mixed so that liquid pools at the surface are avoided.

Some bulking agents are more effective than others in adsorbing the liquids into their pores. These agents tend to minimize emissions by reducing the free liquid area relative to those bulking agents whose particles remain coated with the liquid even after the mixture has been solidified.

In general, bulk liquids or solids should be covered as quickly as is practical. Operations should be planned to minimize the exposed area and time of exposure. Temporary covers (tarpaulin or plastic covers) can be put in place to reduce emissions until it is time to place the daily cover layer.

3.2 Temporary Cover Practices

The next set of operating practices refers to means of reducing emissions through the temporary cover. One fairly obvious means is to utilize thicker covers than required by other constraints. Emission through a cover is inversely proportional to the thickness. Doubling the thickness would have the emission rate. It would also double the material cost of the cover and would reduce the effective volume of the landfill by taking up space that would otherwise be filled with waste materials.

A second and perhaps more effective approach to reduction of emissions is to reduce the air filled porosity, and thereby, the effective diffusivity of volatile materials. Substantial reductions over normal operating practice can be obtained by choice of cover material, compaction practices, and moisture control, as diffusion through the cover depends on the percentage of the void volume that is air filled. Voids are empty spaces remaining in compacted soils because the shape of the individual particles prevents every space from being filled. Table V-1 shows a ranking of a variety types of soils according to several different functions (EPA, 1979). The most effective soils are those with very high clay content. Unfortunately, clays may not be found at or near the site, may be expensive to import, and have poor handling properties. Clays can be mixed with naturally occurring soils so that the overall permeability is decreased substantially without loss in the workability of the resulting materials. Figure V-1 and Table V-2 show the effective permeability relative to the permeability in air, based on Farmer's equation, for a series of soils as a function of water content. The different curves correspond to soils with dry porosity (ε_T) ranging from 0.4 to 0.8. The curve for the least porous soils ($\varepsilon_T = 0.4$) correspond to clays and mixes of clays and other soils.

The curves show several other features. Diffusivity can be decreased by compacting the soil at a given water content to more dense or less porous levels. Compaction is a function of the soil grain size distribution and types of materials present, the weight of the earth-moving equipment used to compact the soil, the number of passes, and the soil moisture content. Figure V-2 shows the relationship, for several soil types, between density and moisture content corresponding to a standard laboratory test method (EPA, 1979). The curves shown correspond to the so-called standard compaction test. The maximum density shown in the curve is called the standard Poctor density. It is also called the standard AASHTO density, because the American Association of State Highway and Transportation Officials has adopted the same test procedure used to generate these standard curves. The moisture content corresponding to the maximum density point is denoted the standard optimum moisture content. The line noting the zero air void curve (S = 100%) represents the dry density (and water content) of soil completely saturated with water at various degrees of compaction.

Soils can generally be compacted to a higher degree than shown in the standard Proctor test through the use of heavier compacting machinery. Depending on the type of soil, increases in density of between 10 and 20% can be obtained by using the modified technique relative to the standard technique. The laboratory test results should be reproducible in the field through the use of heavier compacting machinery. Changes in density of the order of 10 to 15% can be achieved. At a water content of about 15 lbs/cubic foot, this level of compaction can reduce the effective diffusivity by from 50 to 100%.

Even more dramatic reductions in effective diffusion can be obtained by adjusting water content to reduce the air filled porosity to essentially zero. The appropriate water content is that along the zero air voids curve in Figure V-2. Although it is in theory possible to reduce porosity to zero, this objective may simultaneously produce deleterious effects in handling and workability properties. On the other hand, the sharp increase in diffusivity as water content

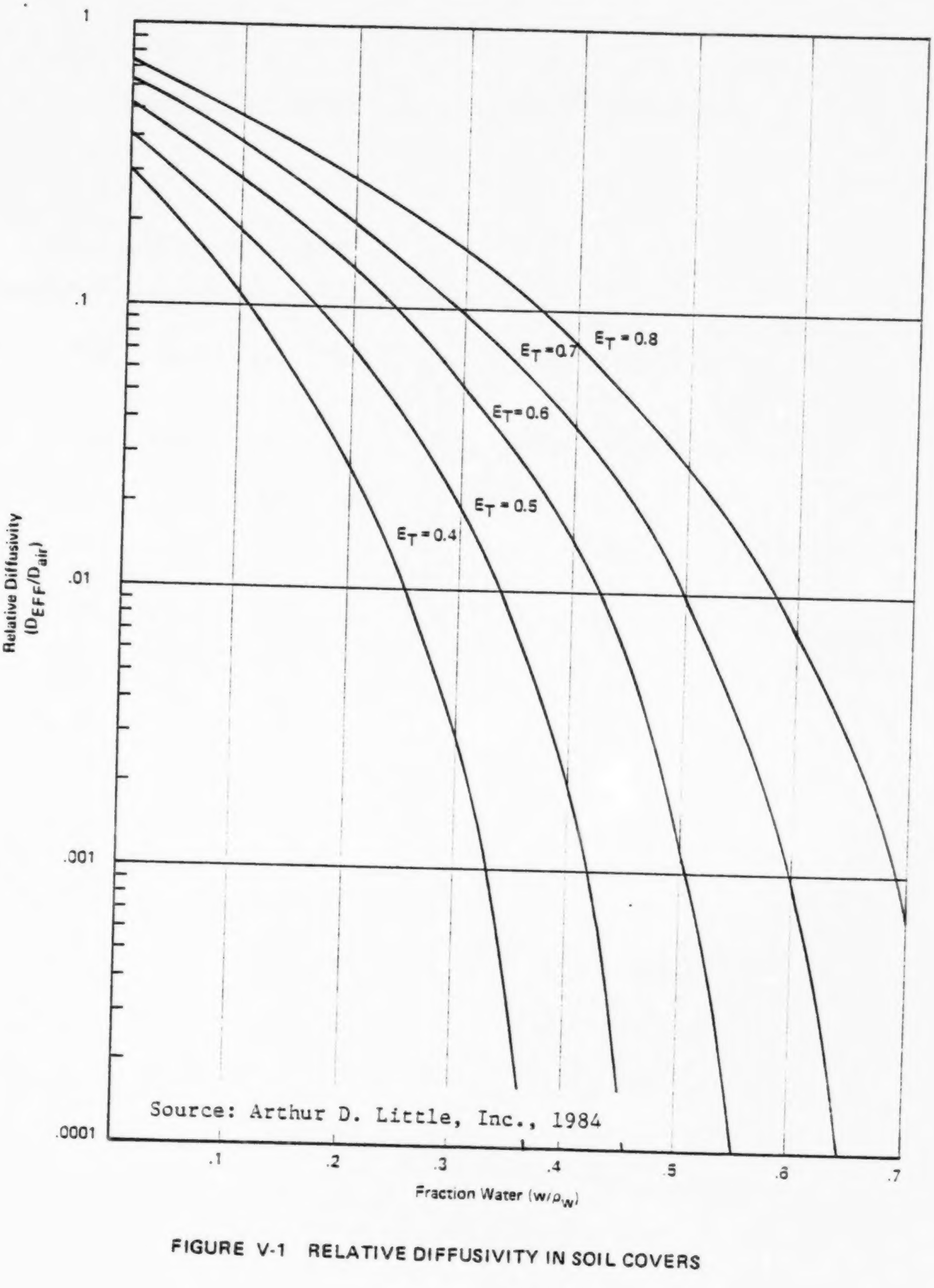
TABLE V-1

RANKING OF USCS SOIL TYPES ACCORDING TO PERFORMANCE OF COVER FUNCTION

USCS Symbol	Typical Soils	Trafficability	Water Infiltration		Gas Migration		Erosion Control		Crack Resistance	Support Vegetation
			Impede	Assist	Impede	Assist	Water	Wind		
GW	Well graded gravels, gravel-sand mixtures, little or no fines	E	F	G	F	E	E	E	E	F
GP	Poorly graded gravels, gravel-sand mixtures, little or no fines	E	P	E	F	E	E	E	E	F
GM	Silty gravels, gravel-sand-silt mixtures	G	F	F	F	G	G	G	G	F
GC	Clayey gravels, gavel-sand-clay mixtures	G	G	F	G	F	G	G	G	G
SW	Well-graded sands, gravelly sands, little or no fines	E	F	G	F	G	E	E	E	F
SP	Poorly graded sands, gravelly sands, little or no fines	E	P	E	F	G	E	E	E	F
SM	Silty sands, sand-silt mixtures	E-G	F	G	F	G	F	G	E	E
SC	Clayey sands, sand-silt mixtures	G-F	F	F	G	F	F	F	G	E
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands, or clayey silts with slight plasticity	G-F	G	F	G	F	P	F	G	G
CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays	F	E	P	E	F	P	F	F	F
OL	Organic silts and organic silty clays of low plasticity	F	-	-	-	-	P	F	F	G
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts	F	G	F	-	-	F	F	F	G
CH	Inorganic clays of high plasticity, fat clays	F	E	P	E	F	F	F	F	F
OH	Organic clays of medium to high plasticity, organic silts	P	-	-	-	-	F	-	F	F
Pt	Peat and other highly organic soils	P	-	-	-	-	G	-	-	G

Key: E = Excellent; G = Good; F = Fair; P = Poor

Source: EPA, 1979.



Source: Arthur D. Little, Inc., 1984

FIGURE V-1 RELATIVE DIFFUSIVITY IN SOIL COVERS

TABLE V-2

RELATIVE DIFFUSIVITY[1] AS A FUNCTION OF SOIL POROSITY

Water Content (w) (lb/ft^3)	Relative Water Fraction (w/ρ_w)	Total Porosity (ε_T) 0.3	0.4	0.5	0.6	0.7	0.8
0	0	.20	.29	.40	.51	.62	.74
6.24	0.1	.052	.11	.19	.28	.37	.48
11.5	0.2	.005	.029	.072	.14	.20	.28
18.7	0.3	0	.0029	.019	.052	.096	.16
25.0	0.4	-	0	.0019	.014	.037	.073
31.6	0.5	-	-	0	.0012	.0096	.028
37.4	0.6	-	-	-	0	.00095	.0072
43.7	0.7	-	-	-	-	0	.00072

1. $\frac{D_{eff}}{D_{air}} = \frac{(\varepsilon_a)^{10/3}}{(\varepsilon_T)^2}$ and $\varepsilon_a = \varepsilon_T - \frac{w}{\rho_w}$

Source: Arthur D. Little, Inc.

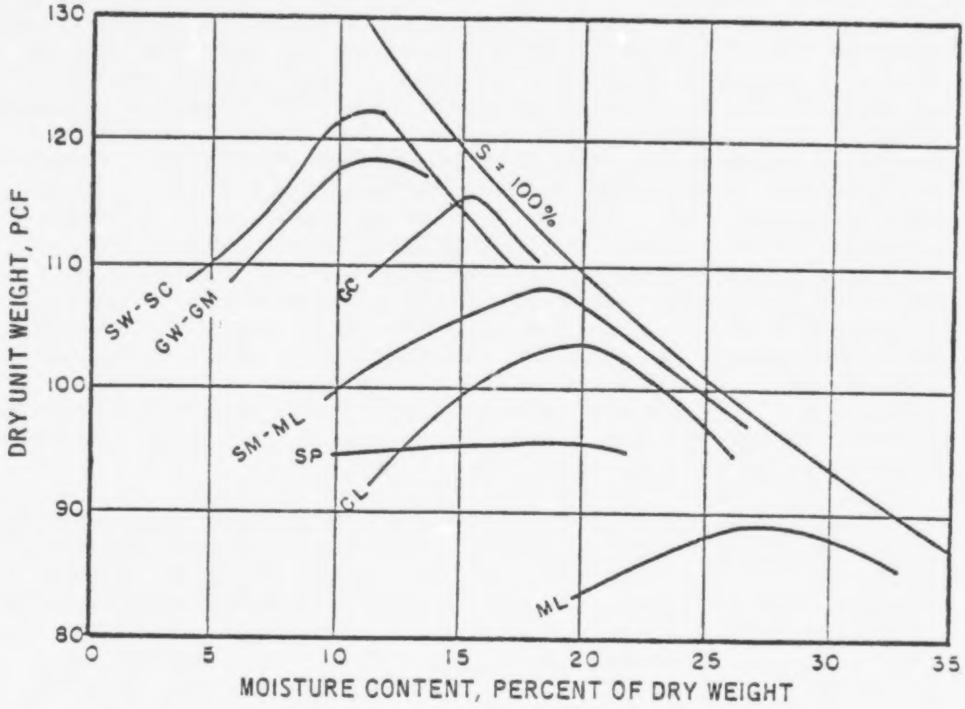


FIGURE V-2 EXAMPLE STANDARD COMPACTION CURVES FOR VARIOUS SOIL TYPES

Source: U.S. Environmental Protection Agency, 1979

decreases demonstrates the need to prevent drying out. Very large relative increases in diffusivity occur as the moisture content begins to fall much below the optimum point.

3.3 Final or Permanent Covers

When a working cell at a hazardous waste landfill has been filled up to its capacity, that portion of the landfill is closed. Closing involves the installation of a cover or cap over the top of the collected wastes to serve many purposes. These include the prevention of infiltration of surface water, the reduction of gaseous emissions, general site security, and others. The current regulations for landfills focus on the problem of groundwater protection and emphasize infiltration control and leachate collection as a means to achieve this objective. Fortunately, from an emissions point of view, this objective also serves as an implicit gaseous emissions control. Covers that are effective in reducing water infiltration are also effective in reducing emissions. Both gas and liquid permeability of porous media such as compacted soils depend in a complex manner on the porosity. Similarly, synthetic membrane covers which are essentially impermeable to liquid water are resistant to volatile vapor permeation. They are not, however, impermeable, and thus, there will always be some residual level of emissions even when a synthetic membrane cover has been installed.

The installation of covers does not eliminate the generation of gases. Gas generation continues through the volatilization of organic wastes and in some settings through the generation of methane as a product of anaerobic degradation. These gases will gradually build up in the landfill and may, if sufficient pressure is generated, damage the cover. At the same time because of the increased pressure, the gases will tend to diffuse laterally out of the landfill and ultimately to the surface. Some sort of vent system is often installed in conjunction with the cover in order to prevent either of these two situations from arising.

The discussion above on temporary covers describes the basic behavior of soils relative to permeability. In designing and installing a permanent cover, there is considerably more flexibility than is possible in temporary covers. The economics permit a much wider choice of materials and complexity of design. In particular, layered designs are becoming quite commonplace. The designer can incorporate favorable trafficability, water impermeability and gas barrier properties are using different materials rather than suffering the trade-offs intrinsic in the use of a single material. Figure V-3 (EPA, 1979) illustrates the concept of layering. In even more complex systems, synthetic membranes may be added in addition to the various soil layers.

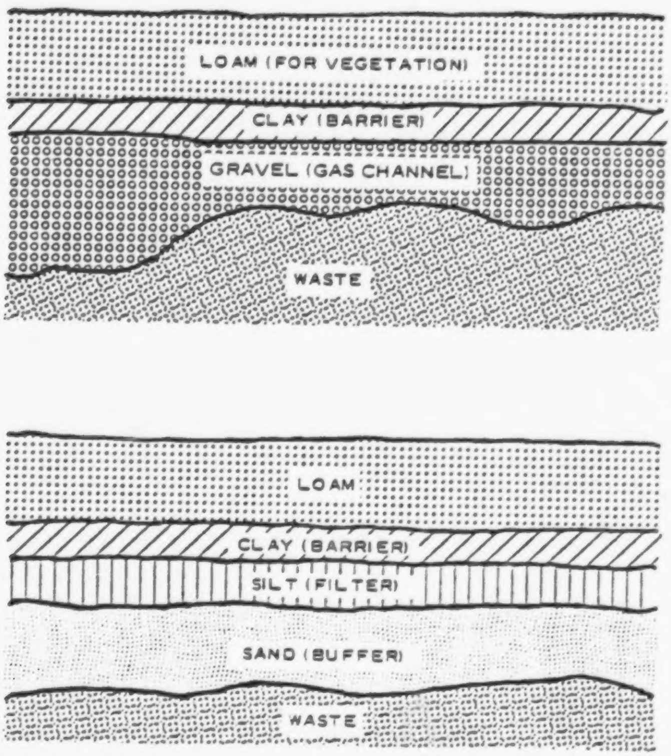


FIGURE V-3 TYPICAL LAYERED COVER SYSTEMS

Source: U.S. Environmental Protection Agency, 1979

The gas channel shown in the figure is installed for use with some sort of vent system to control lateral gas migration. Several technologies can be used:

- o Trench vents. Trench vents are narrow trenches backfilled with sand, gravel and/or stone. They are often lined on one side and can be open to the atmosphere or capped with clay and fitted with laterals and riser pipes vented to the atmosphere. They can also be connected to a negative pressure fan for forced withdrawal.
- o Vertical barriers. Vertical barriers include slurry walls, grout curtains, and synthetic liners.
- o Forced wells. Forced wells for lateral migration control are identical to those for vertical control, except that they are placed around the perimeter of the site and spaced such that all gas is drawn to the wells before crossing the site boundary.
- o Injection trenches and wells. These are similar to forced induction trenches and wells, except that a blower is used to force air into the system. This creates a pressure gradient in the landfill, causing gas to flow away from the system, and thereby preventing lateral migration across the boundary.

In installations where the principal purpose of the gas control system is to prevent damage to the cover, the vapors released directly into the atmosphere. For emission control purposes, some sort of treatment would be added.

4. In-Situ Controls

None of the controls considered are classed as in-situ controls.

5. Post-Treatment

Post-treatment involves the collection of gaseous emissions from the landfill and treatment of those emissions to remove or destroy the volatile organic components. Such systems consist of the collection means and the treatment means. Combinations of external covers and treatment techniques such as carbon adsorption or incineration have been discussed above in the chapter on Surface Impoundments. This approach can be used on landfill operations in essentially the same manner as that for surface impoundments. As previously discussed, air inflated structures can be installed over closed or operating landfill sections covering the typical range of sizes from a fraction of an acre to as much as 5 or 6 acres. These types of structures can include complicated vehicle air locks to permit access during the operating phase.

The air introduced to support the structure, which in conventional systems escapes by permeating through the material, would in this application be exhausted through a series of vents connected to the treatment system. The exhaust gases containing vapor released from the surface of the landfill would be released to the atmosphere after passing through the treatment system.

The installation of a cover serves other purposes as well as providing a means for emissions control. The principal reason for the installation of a cover at the CECOS facility in Livingston, Louisiana, is to keep precipitation out. An alternative control approach with comparable performance would be a treatment system connected directly to gas vents installed within the landfill and exiting through the cover. Forced vents would be used to provide a driving mechanism for introducing gases into the treatment unit and for achieving high collection within the landfill.

D. Effectiveness

1. Introduction

This section presents information pertaining to the effectiveness and costs of the various control approaches. The methodology is slightly different from that used for surface impoundments. For landfills there is no simple way to establish an uncontrolled reference case. Every landfill has some sort of cover but the emission rate through the covers varies potentially over several orders of magnitude. Therefore, comparisons based on percent reduction are arbitrary and depend markedly on the choice of reference. Cost-effectiveness is, however, examined on the basis of cost per pound of emissions removed.

2. Effectiveness

2.1 Covers

Little or no data describing emissions through landfill cover systems under field conditions have been collected. As an alternate means to examine the effectiveness of covers, data based on the Farmer equation described above have been developed to demonstrate the relative effectiveness of different types of cover systems. Table V-3 and Figure V-4 present data for a number of combinations of soil covers of different total porosity at varying water contents. Both are expressed in terms of unit emissions through a 12-inch cover. Unit emissions are the pounds per hour of emissions per square foot per pound per cubic foot of vapor concentration on the bottom side. Diffusivity was assumed to be 0.28 ft^2/hr, a figure typical of a wide range of organic compounds in air. The porosity and percent water vary over the conditions that would be expected at a wide range of landfill operations and locations. The unit emissions are inversely

TABLE V-3

UNIT EMISSIONS[1,2] THROUGH 12-INCH SOIL COVERS FOR SOILS OF DIFFERENT DRY POROSITY

	Unit Emission (ft/hr)			
	Dry Porosity (Bulk density)[4]			
% Water[3]	0.3(118)	0.4(101)	0.5(84)	0.6(67)
0	.056	.083	.111	.142
5	.016	.039	.069	.10
10	.0020	.015	.039	.073
15	.0000032	.0036	.020	.050
20	-	.00033	.0084	.032
25	-	-	.0027	.020
% Moisture at Zero Porosity	15.8	24.7	37.1	55.8

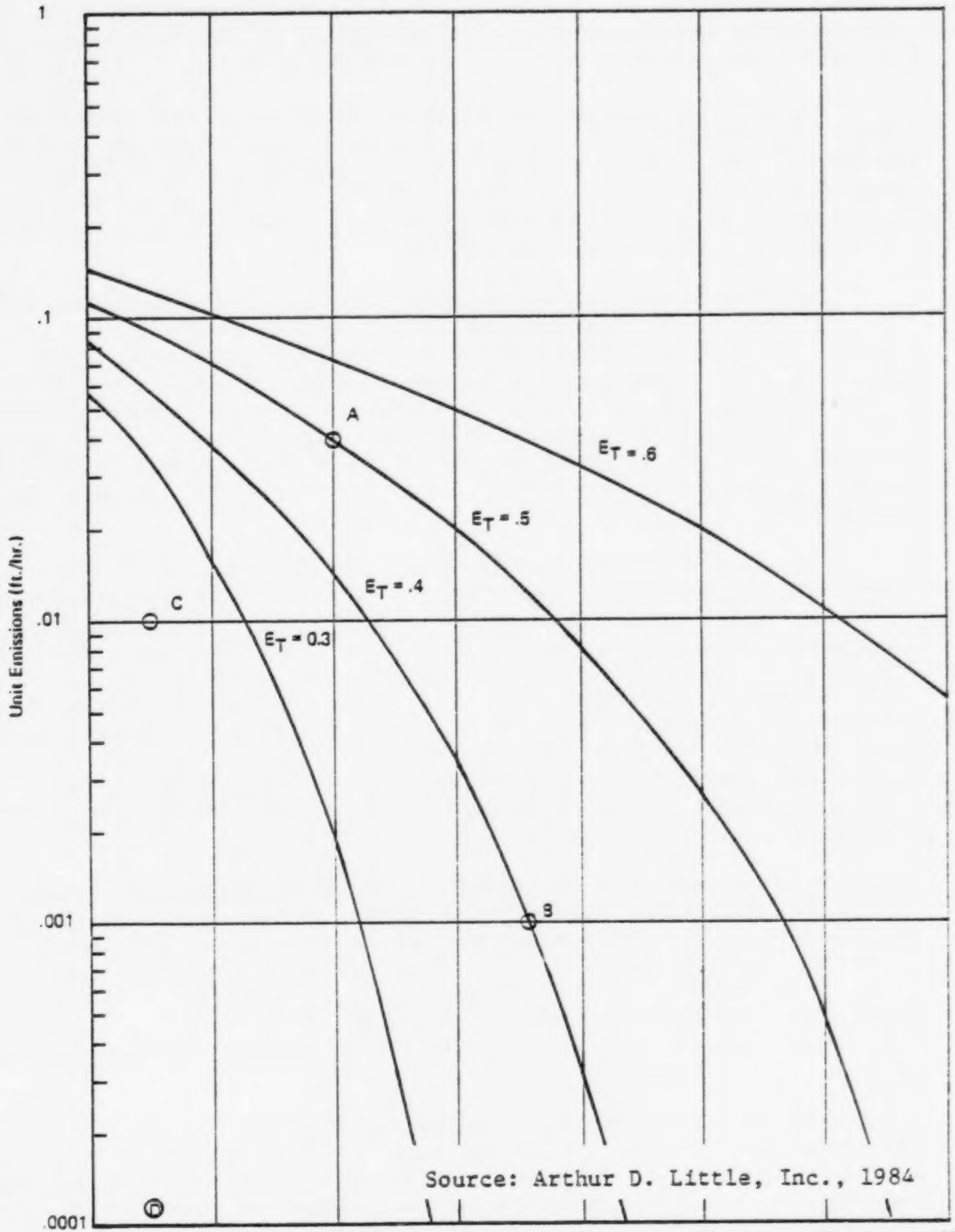
1. Units are $\frac{lb}{ft^2\text{-}hr} / \frac{lb}{ft^3}$ or ft/hr; $\frac{Q}{AC} = \frac{D_{air}}{t} (\varepsilon_a)^{10/3} / (\varepsilon_t)$

2. Diffusivity in air = 0.28 ft^2/hr; t = 1 ft;

3. Percent of dry weight

4. Bulk density (lb/ft^3) in the parentheses, based on particle density = 2.7

Source: Arthur D. Little, Inc.



Source: Arthur D. Little, Inc., 1984

FIGURE V-4 UNIT EMISSIONS THROUGH 12" SOIL COVER OVER A LANDFILL

proportional to cover thickness. For a 6 inch cover, the data shown in the table and figure should be multiplied by 2. Conversely, for a 24-inch cover, these data should be divided by 2.

Figure V-4 shows the extreme sensitivity of emissions to conditions in the soil. For a given soil type compacted to a given porosity, the emission rate can vary over several orders of magnitude depending on the percent of water. In the steeper part of the curves, a change in only a few percentage points in water content can make a substantial change in emission rates.

The reduction in emissions along any one of the curves in Figure V-4 is due to the displacement of air filled voids in the soil by water. At some point, the pores will become completely filled with water and the emissions will become essentially zero. The moisture content corresponding to pore saturation is indicated at the bottom of Table V-3. Under saturated conditions, organic compounds can diffuse through the water in the pores. The rate of this process is very slow compared to the rate through air and has been assumed to be negligible.

The extreme sensitivity to conditions illustrated in the curves indicates the critical significance of choice of cover material, compaction practices, and moisture control in achieving high levels of emissions control when using soil covers. In most cases, the choice of daily cover materials is made on economic grounds with the result that materials excavated from the site or available from nearby sources are generally used. It may be fortuitous that these materials have properties desirable from an emissions control point of view. If not, the properties can be altered to provide lower porosity and higher moisture retaining properties by mixing in relatively small amounts of clay or clay materials.

Moisture control is perhaps the most important factor in emissions reduction. But little attention is generally given to moisture control. Cover materials are often piled up uncovered in an inactive portion of the site. The moisture content, under this practice, depends on the recent weather patterns. To minimize emissions, daily cover materials should be as wet as possible relative to the maintenance of mechanical properties appropriate to workability and structural integrity.

Soil, synthetic membrane, or combinations of the two can be used for permanent covers. As is the case for soil materials, there are little data available for vapor permeation through synthetic membranes of the type and configuration used as covers or liners. Table V-4 presents data recently reported on permeation rates for a variety of materials for several different organic chemicals. The data shown in this table have been converted into the same units used to display the soil cover characteristics above. Permeation rates through all polymeric materials is highly dependent on the chemical nature of the diffusing compound. Polar compounds such as acetone generally behave

TABLE V-4

UNIT EMISSIONS THROUGH MEMBRANE CAPS[1]

HIGH DENSITY POLYETHYLENE - 30 MILS

Xylene	-	0.011
Acetone	-	0.00028
Chloroform	-	0.0071

TEFLON - 4 MILS

Xylene	-	0.000008
Acetone	-	0.00063
Chloroform	-	0.0027

[1] Units are $\frac{\text{lb}}{\text{ft}^2\text{-hr}} / \frac{\text{lb}}{\text{ft}^3}$

Source: Arthur D. Little, Inc. based on data in Haxo, H. et al., 1984.

quite differently from hydrocarbons such as xylene or chlorinated hydrocarbons such as chloroform. In the 30 mil polyethylene membrane the permeation rate of xylene is about 50 times that of acetone, but in a 4 mil Teflon membrane, the ratio is reversed. Acetone passes through the Teflon membrane at about 100 times more rapidly than xylene, but Teflon remains more effective in absolute terms.

It is important to note that the magnitude of these permeabilities fall within the range obtainable with soil covers. Four points have been indicated on the Figure V-4 above to represent typical temporary and permanent soil cover conditions and 2 membranes. Points A and B respectively are located at points corresponding to conditions that might be expected in a temporary soil cover and at a permanent cover. Point C and D represent the permeability of a neoprene and a higher performance material such as Teflon, respectively. The synthetic materials which are often characterized as impermeable are in theory of the same order of effectiveness as properly designed and maintained soil covers. And, if water content is maintained at the saturation point, soil covers can theoretically reduce emissions essentially to zero (neglecting liquid phase diffusion), a level unattainable with the polymeric materials commonly used in today's practice.

Composite membranes including a layer of Mylar, a polyester polymeric material, can achieve vapor permeation rates that are effectively unmeasurable. These materials have been used in developmental applications in food containers and in special protective fabrics. (Personal communication, A. Schwope). Laminates in forms suitable for field application as permanent cover materials are presently unavailable.

As components of permanent covers, synthetic membranes have several advantages relative to soils. Once installed, they require little maintenance to maintain their efficacy. Performance over long periods of time is, however, uncertain. The materials may degrade and if this occurs, would have to be replaced. In practice, cracking and nonhomogeneities in the materials could significantly reduce the effectiveness relative to the design values. Small fissures in a cover would act as conduits for the vapors generated within a large area of the landfill in the vicinity of the crack. Careful maintenance of the cover including vegetation to prevent erosion, and installation of sprinklers to maintain moisture content at uniform levels will reduce the probability of the formation of cracks. The roots of plants must be prevented from penetrating the gas barrier.

Maintaining appropriate moisture levels is, however, inconsistent with groundwater protection objectives at a landfill. Downward infiltration of water and prevention of leachate formation is a primary objective for covers from this point of view. Combinations of a soil cover and membrane can be designed to achieve both sets of objectives.

Although with soil covers zero emission is possible and desirable, it is more likely that the cover system will exhibit a finite emission rate. Table V-5 shows the quantity of emissions per year through an acre of surface corresponding to the four cover systems depicted as points A, B, C, and D, in Figure V-1 above. Emissions are given for a range of vapor concentrations in the landfill. The table indicates that, even with high performance covers in place, considerable loss of high vapor pressure compounds can occur. Volatile solvents such as MEK or benzene have equilibrium vapor pressures of the order of 100,000 parts per million at ambient conditions. Such compounds if present in relatively undiluted form could be emitted in the range of several metric tons per year for soil of quite low permeability. Neoprene which is often considered a suitable cover material (EPA, 1979) could permit emissions of about an order of magnitude greater.

Emissions in existing closed facilities where cover systems are not as effective as those corresponding to the characteristics discussed above could be emitting substantial quantities of volatile organics at present. These emissions could be reduced by replacement of cover systems with more effective designs or by the installation of one of the post-treatment systems discussed in the next section.

2.2 Post-Treatment

Covers alone may not be capable of achieving desired performance levels. Covers do not reduce the total quantity of emissions ultimately entering the atmosphere. As long as there is some finite permeability, emissions will continue to enter the atmosphere until all the materials in the landfill have diffused into the atmosphere. For very effective covers the time period may stretch out over hundreds of years. Post-treatment offers a means to reduce the quantity of volatile materials reaching the atmosphere by removing them from the gases that are formed in the landfill or from the atmosphere above the landfill. Two types of post-treatment were discussed above, the systems employing vents to collect the vapors and systems employing external structures to capture the gases. Either configuration plus adsorption system, incineration, or other gaseous control means can be used. The effectiveness depends primarily on the collection system. The treatment portion can achieve high levels of efficiency exceeding 95%. The effectiveness of an external cover depends on the integrity of the cover and permeability of the materials used.

Forced induction trench vents with risers and laterals are the most effective lateral control method if the trenches extend to groundwater or to bedrock. Forced well systems may be somewhat less effective, but may also be less expensive and useful at greater depth. Natural induction wells and trenches have not been effective in many situations. The effectiveness of vertical barriers (including lined trenches) and injection systems is expected to be good, but experience is limited. The integrity of grout curtains and vertical liners as gas barriers may be difficult to achieve and maintain.

TABLE V-5

ANNUAL EMISSIONS

Vapor Concentration (ppmv)	Emissions (lb/year-acre) Daily Cover A	 Final Cover B	 Neoprene Cap C	 Laminate Cap D
10	42	1.0	10.5	0.1
50	210	5.3	53	.53
100	420	10.5	105	1.05
500	2100	53	530	5.3
1000	4200	105	1050	10.5
5000	21000	530	5300	53
10000	42000	1050	10500	105
50000	210000	5300	53000	530
100000	420000	10500	105000	1050

Notes:

1. A, B, C, D refer to points on Figure V-4.

Source: Arthur D. Little, Inc.

Controls for lateral gas migration should extend to bedrock or the water table to be effective. This prevents gas from migrating underneath the control mechanism. When depth of bedrock and the water table is greater than 20 to 30 feet, forced induction wells may be the only effective control strategy.

Forced induction trenches and wells can be designed in a manner similar to wells for control of vertical migration. Forced trenches (i.e., forced induction through riser pipes) are effectively the same as wells completed in gravel. The radius of influence of the wells will therefore be greater, allowing greater spacing.

3. Costs

3.1 Pretreatment

The same unit costs used in the section and surface impoundments were used. Pretreatment costs taken from Spivey et al., (1984) are in the range of $1.00 per pound ($2,000/Mg) of waste removed from an incoming waste stream. Cost of other controls are compared to a range of pre-treatment costs to reflect variations due to waste stream properties, treatment type, size, and overall system design.

3.2 Design and Operating Practice

Installed cover system cost estimates are shown in Table V-6. (EPA, 1979). Membrane cover layers are 4-8 times as expensive as soils. Costs depend on many site specific factors. This table should be considered only as a basis for comparative analysis, not as a basis for design and selection of a cover system at a particular site.

Costs for moisture control have not been estimated. Incremental costs for operating practices that will reduce atmospheric emission should be quite small. Costs may include annualized capital costs for heavier earth-moving equipment than would conventionally be used. Extra labor might be required to achieve higher compaction if extra passes were performed. Moisture control should require little additional labor. Using special imported temporary cover materials or additives would increase the costs of soil covers over that shown in the table.

3.3 In-Situ Controls

No in-situ controls are included in the analysis of landfills.

3.4 Post-Treatment

Costs for cover structures plus post-treatment were developed above in the discussion of surface impoundments. The costs are summarized in Table V-7. Treatment costs are based on non-regenerative carbon adsorption or incineration without heat recovery.

TABLE V-6

ESTIMATED UNIT COSTS FOR SOME COVER LAYERS

Layer Type and Thickness	Installed Cost dollars/yd^2
Loose soil (2 ft)	0.35
Compacted soil (2 ft)	0.70
Cement concrete (4 in.)	9.00
Asphalt concrete (4 in.)	2.50-3.50
Soil-cement (7 in.)	1.50
Soil-asphalt	1.50
Polyethylene membrane (10 mil)†	1.00-1.50
Polyvinyl chloride membrane (20 mil)	1.30-2.00
Chlorinated polyethylene membrane (20-30 mil)	2.40-3.20
Hypalon membrane (20 mil)	2.50
Neoprene membrane	5.00
Ethylene propylene rubber membrane	2.70-3.50
Butyl rubber membrane	2.70-3.80
Paving asphalt (2 in.)	1.20-1.70
Sprayed asphalt membrane (1/4 in.) and soil cover	1.25-1.75
Reinforced asphalt membrane (100 mil) and soil cover	1.50-2.00
Bentonite layer (2 in.)	1.40
Bentonite admixture (9 lb/yd^2) in soil	0.75

† Not recommended because of thinness.

Source: U.S. Environmental Protection Agency, 1979

TABLE V-7

POST-TREATMENT COLLECTION SYSTEM COST ESTIMATES[1,2]

	Size of Facility			
	0.4 Acre		6 Acre	
	Capital	Annualized[3]	Capital	Annualized
Air-Supported System	$150,000	$24,000	$1,600,000	$250,000
Pipe Vents	80,000	12,000	403,000	60,000
Compacted Soil Cover	2,000	500	28,000	5,000
20-Mil Hypalon Cover	6,500	1,500	96,000	15,000

Note:
1. Treatment costs must be added to the figures shown.
2. Cost in 1982 dollars.
3. Annualized costs include a capital contribution (based on a 10-year life and 10% interest) and typical O&M costs.

Source: Arthur D. Little, Inc.

Costs for a post-treatment system based on collection by means of vents coupled to carbon adsorption or incineration are also shown in Table V-7. The costs are based on a pipe vent system. Pipe vents include the blowers required to drive a control system. Passive trench vent systems might be used in situations where cover protection is the only function of the gas control. Pipe vents appear better suited for post-treatment applications. The costs presented do not include the cover.

4. Cost-Effectiveness

As noted in the introductory paragraph to this section, definitions of an uncontrolled, reference landfill is rather arbitrary since covers are required by regulations, but vary widely in performance. Thus, it is not meaningful to compare cover performance to other operating controls on the basis of pounds of volatiles removed.

Notwithstanding that analytic problem, operating practices involving covers may be extremely cost-effective, that is, providing significant emissions reduction for little incremental cost. The earlier discussion describing emission rate as a function of cover properties indicates that several orders of magnitude or more improvement in performance may be attainable with careful practice. The costs to achieve this performance can be quite low. Moisture control of daily cover and grain size modifications by adding soil conditioners, clays, etc., are not expensive relative to the basic operating costs at a landfill. Under these circumstances, the cost-effectiveness would be high, compared to pretreatment, for example, expressed as pounds of volatile reduction per dollar. Even the added cost of heavier earth-moving equipment to achieve denser compaction should not change the cost-effectiveness very much.

The use of permeability reducing techniques for permanent covers should be similarly cost-effective compared to conventional design approaches. Low vapor permeability soil and synthetic membrane covers do not represent significant incremental costs. Design requirements for covers are established currently by regulations designed to reduce or prevent surface water infiltration. Incremental costs to maximize gas control performance are small.

Combination covers appear most effective. Although permeability in soil covers can, in theory, be reduced to zero, it would be extremely difficult to achieve perfect performance in practice. Imperfections in soil covers, particularly in large cells, are more or less inevitable. Maintaining high moisture content runs counter to control of water infiltration. Adding a synthetic membrane could offset these practical difficulties without significant incremental costs. The cover would prevent water infiltration from penetrating into the closed cell, and would act as a seal to inhibit permeation through cracks in the soil layer.

Even as performance approaches the theoretical limit, there are two factors which suggest the potential applications of alternative controls. First, as noted, practical performance may not reach theoretical levels. There are no data currently available to estimate the departure from theoretical performance. Second, covers only retard the loss of materials from the landfill. Little decay occurs in hazardous waste landfills so that, with any finite permeability, wastes will continue to enter the atmosphere. The applications of pre- or post-treatment can remove volatiles permanently.

Pretreatment costs are less than post-treatment for landfills as they are for other kinds of disposal facilities. Thus, unless there is some technical reason that pretreatment would not be practical, post-treatment would not be the cost-effective choice. Pretreatment costs are expected to be less than five dollars per pound of waste removed (1-2 dollars/per pound have been used in comparison, above). Post-treatment costs are expected to exceed about five dollars per pound removed plus the costs of the collector (cover or vent system). Thus, pretreatment would always be preferred. Covers serve more than one purpose; keeping out rain as well as keeping in volatiles. If the costs can be allocated to several purposes, post-treatment, using covers, would appear more cost-effective.

E. Summary

Cover design and maintenance present the most cost-effective and highest degree of emission reduction potential of all the controls. In theory, emissions can be reduced to essentially zero by maintaining the pores of a soil cover full of water. Synthetic membranes in current use as cover materials all exhibit finite permeability to organic vapors.

Combination cover systems with both soil layers and synthetic membranes may achieve very high performance levels for both vapor and water infiltration control. Combinations can offset practical limitations in soil covers due to cracks and inhomogeneities.

Very little data are available that characterize current practice at operating landfills or at closed, previously active sites. There is, even in this situation, a reasonable expection that past and current practices are poor with respect to vapor control, and so there is substantial opportunity to reduce vapor emissions on a national scale.

Pretreatment eliminates the potential for emissions, but may have limited application to the highly variable wastes that are placed in landfills. Much of the wastes may come from widely dispersed small generators. These conditions limit the practicality of pretreatment.

Post-treatment systems have not been used at landfills, but the recent installation of an air inflated structure at a landfill in Louisiana indicates that this approach can be applied. The critical element in a post-treatment system is the collectors means. Treatment technology is proven but expensive. The covering structure includes air locks to permit vehicle access and prevents rainfall from falling on the site.

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VI. LAND TREATMENT FACILITIES

A. Description

Land treatment involves application of wastes to soil in which natural processes degrade or immobilize constituents in the waste. For organic contaminants, the principal operating mechanisms are volatilization and biological decay supported by microorganisms that are ubiquitously present in all soils. Inorganic constituents are immobilized within the soil through several processes which lead to absorption of the constituents on the surface of soil particles. Land-treatment facilities come in a variety of sizes and shapes. The medium area derived from EPA survey data is approximately 12 acres (Spivey et al., 1984). Sites range from approximately one acre at the low end to several hundred acres at the upper end. A few land treatment facilities are around 1,000 acres in area. EPA survey data indicate approximately 150 sites were operating in 1981, but other sources indicate closer to 200 sites exist (EPA, 1983).

The area at a land treatment facility can be used in several ways. Major site designs are:

- Single Plot - wastes are applied to the entire area at each application.

- Progressive Plot - wastes are applied to a few small subplots until their capacity is reached. These subplots are then closed, and the application progresses to a few more subplots until the entire area is exhausted.

- Rotating Plot - waste is applied to small subplots, which are then cultivated and revegetated. After the wastes have degraded, the plots are reused.

The wastes may be applied to the soil surface in a variety of techniques. The choice of the technique can quite significantly influence the degree to which wastes volatilize. Application technique is the most important operational variable at a land treatment facility. The four major application techniques are:

- Spray Application - liquid waste is sprayed on the surface of the site.

- Surface Application - wastes are dumped on the site surface either in small quantities (that is, waste is spread as it is applied) or in bulk (waste is dumped in one place and spread by plow or other equipment).

- Subsurface Injection - waste is injected at a shallow depth generally ranging from 4-8 inches (10 to 20 cm) into the soil.

- Overland Flow - wastewater is caused to flow over relatively impermeable soil with a slope from about 2 to 8%. This technique is used for treating contaminated run-off or wastewater effluents from industrial processes.

Following the application of wastes to the soil, the wastes may be incorporated into the top layer of soil by standard cultivation techniques. The soil may be tilled several times following a single application of waste before the next application. Typically, the wastes are tilled into the top 4 to 8 inches (10 to 20 cm) of soil.

In some settings the site is revegetated. In this case, the surface is not tilled after each application. This technique is commonly used to treat dilute wastes which can be applied by spray application.

B. Emission Sources and Models

1. General

Emissions to the atmosphere at a land treatment facility arise from two primary sources. The first is pools of liquid wastes which form after application on the surface. These pools remain until the liquids seep into the underlying soils or are incorporated by tilling. Volatilization directly into the atmosphere can occur as long as the liquid wastes are exposed at the surface.

The second source is wastes which have been incorporated into the soil. Volatile constituents in the wastes can enter the interstices and eventually diffuse to the soil surface. At the surface the emissions mix into the atmosphere and are swept away from the site.

2. Emission Models

2.1 Surface Emissions

Emissions from a surface layer of liquids behave in the same general manner as emissions from a floating layer of organic compounds on a surface impoundment. For pure or highly concentrated organic mixes, the following equation describes the emission rate:

$$Q = Ak_g' C$$

where Q = emission rate (lb/hr)

A = surface area (ft^2)

k_g' = mass transfer coefficient (ft/hr)

C = vapor concentrations of diffusing component in equilibrium with liquid, lb/ft^3

$$\text{and } k_g' = k_g \frac{RT}{P_T}$$

where k_g = mass transfer coefficient ($lb\text{-}mol/ft^2$ hr)
R = gas constant ($atm\text{-}ft^3/lb\text{-}mol$ - °R)
T = temperature (°R)
P_T = total pressure (atm)

This equation is appropriate immediately after application of wastes and as long as a liquid pool remains on the surface. It is also appropriate for use in spills generally. The simple form assumes gas film control and is not appropriate for dilute wastes in which diffusion to the liquid surface from the bulk of the pool is significant in determining the overall mass transfer coefficient.

In the discussions below, it is assumed that the hazardous wastes would be tilled into the soil immediately upon application, or would be injected by a subsurface technique. Emissions from surface pools can be quite substantial; they should be avoided wherever possible.

2.2 Emissions from Incorporated Wastes

The model used to estimate emissions from land treatment after the wastes have been incorporated was based on work by Thibodeaux as reported by Hwang, (1982). The equation; for the ith contaminant species, is:

$$Q = AD_{eff} \; C_g \; [h_s^2 + (2 \, D_e \, t \, A \, (h_p - h_s) \; C_g) \; M_o]^{-\frac{1}{2}}$$

where: Q = flux rate (lb/ft^2-hr)

D_{eff} = diffusivity of air filled pore space (ft^2/hr)

= $D_{air} \, \varepsilon_T / \tau$

D_{air} = molecular diffusivity of i in air (ft^2/hr)

e_T = total porosity

τ = tortuosity factor ($\tau \cong 4$).

h_s = depth of surface injection (ft)

t = time after application (hr)

A = surface area of application (ft^2)

h_p = depth of penetration of plow slice (ft)

M_o = initial mass of component i (lb)

C_g = concentration of i on gas side of interface (lb/ft^3)

This model is appropriate once the waste has been incorporated into the soil. It assumes:

- The soil column is isothermal
- No capilliary action
- No adsorption on soil particles
- No biochemical degradation

This rather complex equation becomes much simpler under two separate assumptions. The first assumption is that the waste is placed on the surface and immediately tilled. In this case, h_s equals zero. This equation, rearranged in terms of emissions per unit area is:

$$\frac{Q}{A} = \left[\frac{C_g D_{eff} (M_o/A)}{2 h_p t}\right]^{1/2} = D_{eff}/f$$

where:

$$f = \left[\frac{2t D_{eff} h_p}{C_g (M_o/A)}\right]^{1/2}$$

As long as the assumption of no biodegradation is valid, i.e., for a short time following applications, the Thibodeau-Hwang equation indicates that emissions would decrease proportional to the square root of time expired after application. Once biodegradation becomes important, so that vapor concentration, Cg, decreases with time, the relationship becomes more complex. Emission rate would decrease more rapidly than the inverse square root form indicates. The exact form depends on the nature of the behavior of concentration with time.

The second simplifying assumption is that the wastes are injected at a depth equal to the depth of penetration of the plow or cultivator. In this case, h_s equals h_p and the equation becomes simply:

$$\frac{Q}{A} = \frac{D_{eff}}{h_s} Cg$$

Similarly in this case, the emission rate would remain constant at first and then would decrease according to the functional form of the relationship between concentrations and time.

3. Controlling Parameters

3.1 Liquid Pools

There is virtually no parameter that can be controlled as long as a liquid pool is present. To minimize volatile emission, the time that the liquid are exposed should be kept as short as possible.

3.2 Incorporated Wastes

Emissions, once the wastes have been incorporated, depend on a number of parameters. In all cases, emissions depend in different functional forms on the concentration of the component in the waste. For the case where wastes are injected at the same depth as the plow cut, the initial emissions depends additionally only on the effective diffusivity and depth of injection. The deeper the injection, the lower would be the emission rate. The rate depends directly on effective diffusivity. Diffusivity in the form developed by Thibodeaux and reported by Hwang (1982) is related to the porosity of the soil and a tortuosity factor. Porosity as in the case of covers for landfills depends on the degree to which the soil is compacted and on the moisture content. Unlike the case for covers, it is important to maintain a relatively high soil air-filled porosity in order to provide a means to carry oxygen to the microorganisms that degrade the organic wastes. Porosity is therefore not considered to be a controllable parameter for land treatment.

For surface injections, the initial emission rate depends on the depth of the plow cut, waste application rate, and time (explicitly) as well as effective diffusivity, and concentration (implicit function of time). Emissions decrease inversely with the square root of time following application. In this configuration the rate depends inversely on the square root of plow depth rather than the first power as in the alternative form. Finally, the initial rate depends directly on the square root of the application rate.

The total emissions for a fixed area over a period of time, say a year, depend on the number of applications. A given quantity of waste can be applied as fewer and larger portions or more and smaller portions. The total emissions over the period will depend on the number of applications. The form of the exact dependence requires that the rate equations above be integrated. The integration cannot be carried out analytically, without an explicit form of the relationship between concentrations and time, which depends on the nature of the biodegradation process and on its coupling to the diffusive mechanism. This relationship is complex and poorly understood at present.

The equations were integrated for several possible forms for Cg as a function of time to determine the general shape of the dependency on application rate. The results indicate that total emissions increase with increasing frequency of applications; thus, to control emissions for a fixed quantity of wastes applied over an intended period, the maximum quantity consistent with the biodegradative behavior should be applied each time.

C. Controls

1. Introduction

Emissions from land treatment can be reduced by removal of volatile components of wastes prior to application. Pretreatment will have the same effectiveness for this type of facility as those discussed previously. Post-treatment techniques involving collection systems in conjunction with a treatment process can also be applied. The equations indicate that the rate of emission is quite sensitive to a number of the operating design parameters. There are, as a result, several control methods that involve design and operating practices. There are no available control approaches considered as in-situ methods for this type of facility.

2. Pretreatment

Pretreatment may not be appropriate or effective for land treatment. If the biodegradation processes that occur in the soil produce volatile compounds from the breakdown of heavier molecules, then pretreatment will not be so effective. Pretreatment may be more an alternative to land treatment not an adjunct, since both are designed to handle the same kind of organics.

3. Operating Practices

Volatile emission rate can be controlled through the means by which the wastes are injected and by adjusting the amount applied per unit area per pass. Subsurface injection is considerably more effective in controlling emissions than is surface injection immediately followed by tilling. Wastes should be injected at the maximum depth consistent with the parameters determine the waste degradation rates. Typical common depths of application range from 4 to 8 inches (10-20 cm) below the soil surface (Wooding and Shipp, 1979). A variety of types of equipment have been developed for subsurface injection (EPA, 1983, Overcash and Pal, 1979). In some of these devices, the waste is simultaneously injected below the surface and mixed into the top 6 to 10 inches (15 to 25 cm) of soil. The initial injection may be followed closely by a second pass with a cultivator to distribute the waste uniformly across the treatment area. Monographs discussing land treatment recommend subsurface injection for wastes with volatile components and odorous constituents. Subsurface injection minimizes exposure of the operators during application.

Emission rate is a weak function of the application rate per unit area. For economic reasons, land treatment facility operators apply the maximum waste per unit area consistent with the degradation capabilities and carrying or assimilative capacity of the soils. In practice, application rates often exceed values recommended in conventional design and guidance sources. Emissions increase when the design capacity is overloaded because degradation will be impeded and the volatile materials remain in the soil for longer periods of time. Typical application rates range from about one-half a pound per square foot to about three times that rate. (EPA, 1983)

As noted earlier soil porosity is probably not controllable but care should be taken to prevent excessive drying. If the soil becomes too dry, the effective diffusivity can increase by several orders of magnitude. (See the discussion of landfills for the particulars of the relationship between diffusivity and soil porosity). Soil moisture content should be maintained at the maximum level consistent with the parameters controlling degradation in order to keep atmospheric emissions to a minimum.

4. In-Situ Controls

No in-situ controls are available for land treatment.

5. Post-Treatment

It is conceptually possible to consider placing air inflated structures over small land treatment facilities or over sections of larger facilities. In a manner similar to that described above, air containing the volatile emissions can be vented through a treatment unit prior to being released into the atmosphere. Use of such covers would also give the facility operator some degree of control over temperature and moisture.

D. Effectiveness

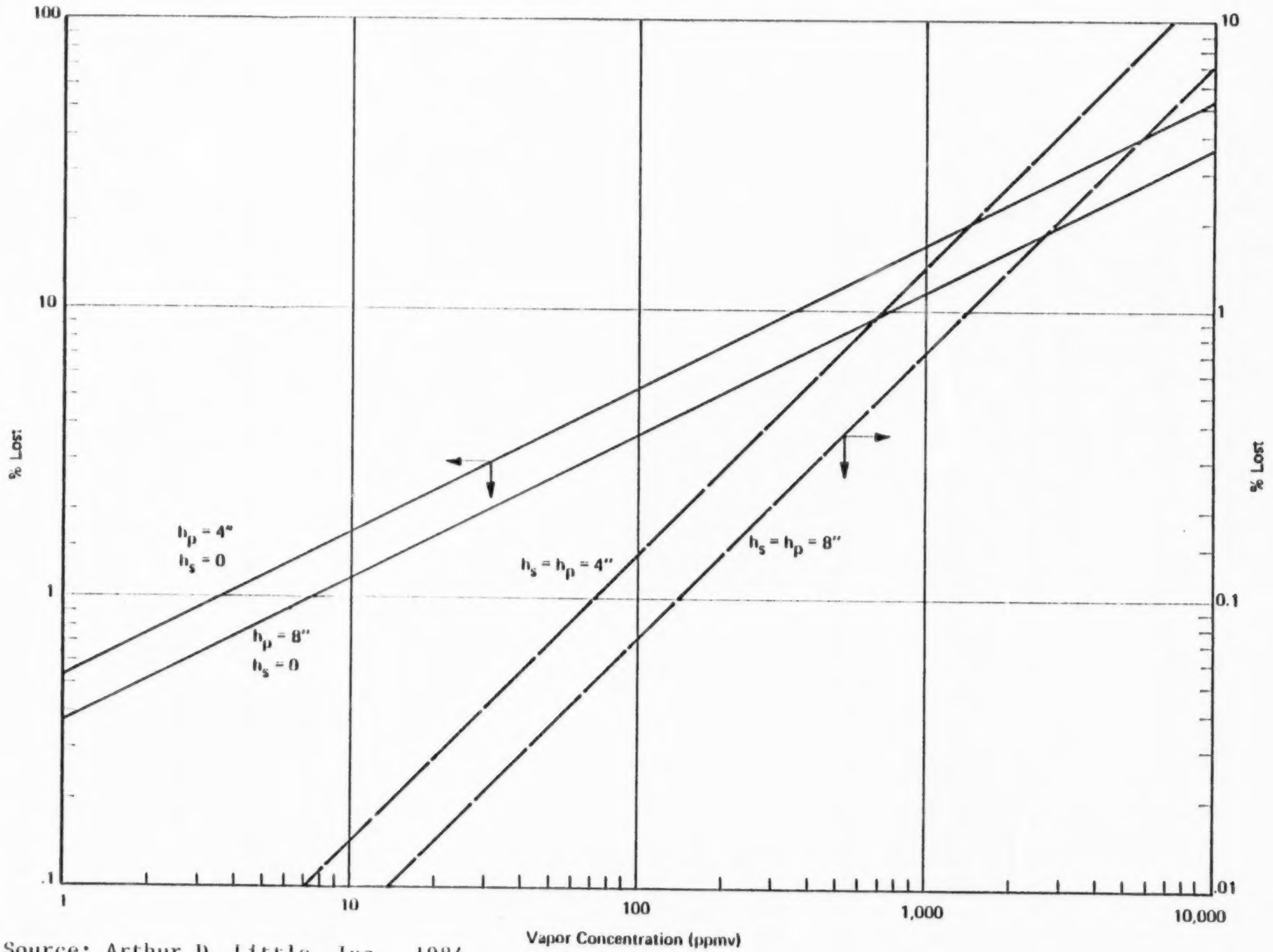
1. Introduction

The effectiveness of controls at land treatment focusses on tilling practices. Pretreatment and post-treatment perform essentially the same as described in the preceding sections. Emissions are referred to surface applications as the uncontrolled case.

2. Emissions Reduction and Effectiveness

Figure VI-1 indicates the percent of volatiles applied in land treatment that would be lost to the atmosphere through volatilization. These curves are based on the equations developed above. The emission loss relationships and the data generated using them assume no biological degradation. This assumption is obviously unrealistic. The main function of land treatment for organic compounds is to provide degradation. The actual emissions and percentage lost to the atmosphere will be less than that depicted herein for this reason. Nevertheless, the equations and the data are useful in describing the relative effectiveness of a variety of alternate controls. The results shown in Figure VI-1 are consistent with data taken in the field. (Minear et al., 1981). As reported in this reference, oil wastes spread and tilled into soil resulted in losses of 0.6% and 2% in two separate field tests (Francke and Clarke, 1974, and Suntech, undated). In another test reported in this same reference, 11% of the wastes from an API separator were lost to the atmosphere (Suntech, undated). In this last test the wastes were spread on the surface but not tilled into the soil. Vapor concentration over the types of wastes treated were not reported. Based on the types of hydrocarbons generally present in the wastes treated, the vapor concentration can be estimated. A value of around 1,000 ppm appears reasonable.

The same kind of data are shown in a somewhat different format in Table VI-1. In this table the quantity of volatile losses per acre per year is shown for compounds of increasing vapor pressure. Comparison of the columns for surface injection versus those for subsurface injection illustrate the reduction that is theoretically possible. Figure VI-2 illustrates the reduction efficiency directly. The potential reductions shown in Table VI-1 and Figure VI-2 may not be achieved in practice, if the rate of biodegradation is reduced sufficiently by subsurface injection. Stated alternatively, if the rate of degradation is slowed down, then there is more time and more unreacted materials available for volatilization. The efficiency depends on the relative volatility of the constituent. Efficiency for low volatility compounds is quite high exceeding 90% for constituents with vapor concentrations below about 1,000 ppm. The efficiency falls off for the more volatile compounds. For reference, the vapor concentration in equilibrium with benzene at normal temperatures is about 100,000 ppm. The corresponding equilibrium concentration for xylene is about 10,000 ppm. The overall effectiveness will depend on the particular mix of compounds in the waste.



Source: Arthur D. Little, Inc., 1984

FIGURE VI-1 PERCENT OF VOLATILES LOST TO ATMOSPHERE

TABLE VI-1

ANNUAL LOSSES FROM 1 ACRE OF LAND TREATMENT[1]

Equilibrium Vapor Concentration (PPMV)[3]	Injection (h_s) and Plow Depth (h_p)			
	$h_s = 0$		$h_s = h_p$	
	h_p = 4"	8"	4"	8"
10	4.8	3.4	.1	.05
50	10.7	7.6	.2	.1
100	15.2	10.7	.4	.2
500	34	24	2	1
1000	48	34	4	2
5000	107	76	20	10
10000	152	107	40	20
50000	287[2]	246	200	100
100000	287[2]	287[2]	287[2]	200

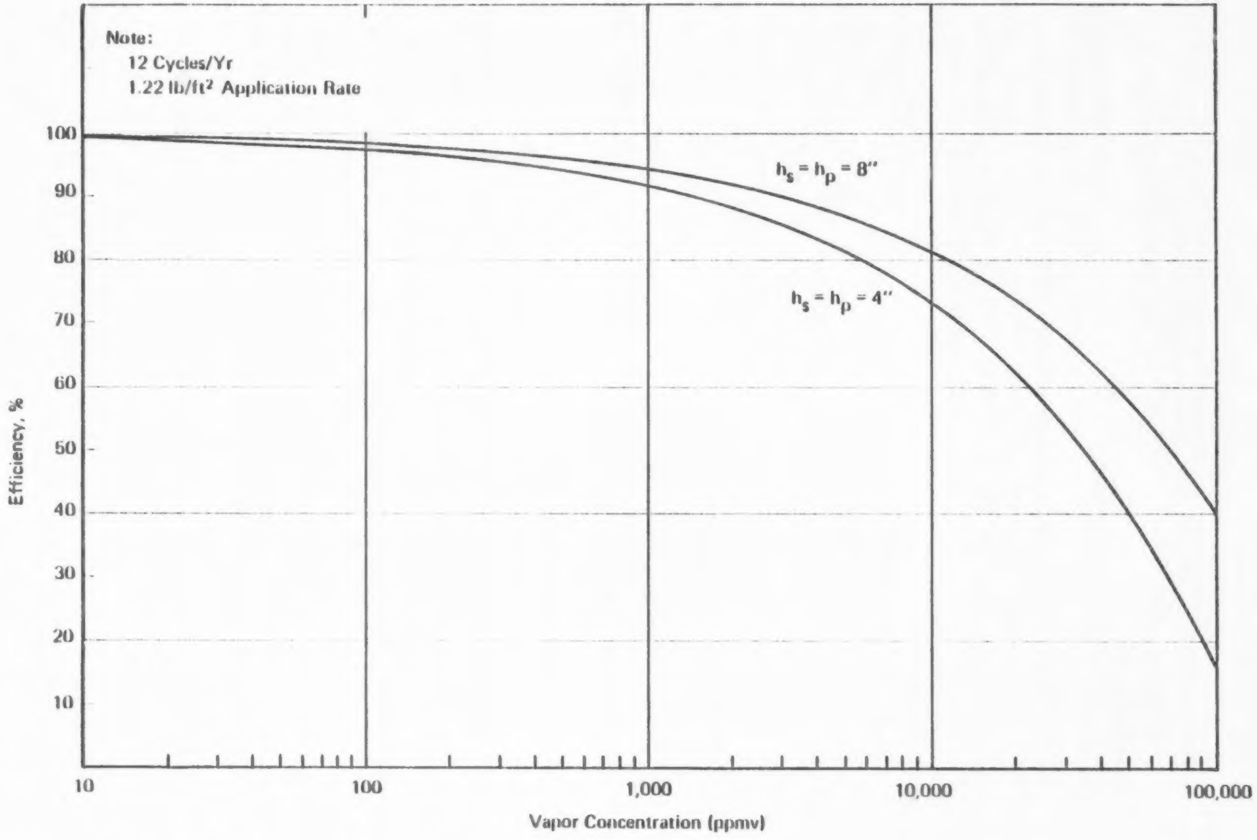
Notes:

[1] Units are metric tons per year; 287 metric tons applied per year

[2] Complete (100%) loss

[3] Parts per million by volume

Source: Arthur D. Little, Inc.



Source: Arthur D. Little, Inc., 1984

FIGURE VI-2 REDUCTION EFFICIENCY FOR SUBSURFACE INJECTION RELATIVE TO SURFACE INJECTION

3. Costs

3.1 Pretreatment

Pretreatment costs are assumed, as above to be of the order of \$1-2 per pound (\$2,200-\$4,400/Mg) of wastes recovered.

3.2 Operating Practices

The more effective subsurface injection technique is only incrementally more expensive than surface application. The addition of injection equipment to a tank truck spreader adds about 7% (about \$5,000) to the cost of the system (Overcash and Pal, 1979). The labor cost should be about the same for either applications technique.

Lower application rates according, to the Thibodeaux relationship, would reduce emissions. This control would be costly as the land required to treat a given quantity of waste would increase proportional to the decrease in application rate. The added cost depends on the cost of land.

3.3 Post-Treatment

Post-treatment using an air-supported cover in combination with carbon adsorption or incineration costs the same as these systems described in the previous chapters.

4. Cost Effectiveness

Based on the model used herein, subsurface injection is the most cost-effective emission control for land treatment facilities. Predicted efficiency of reduction ranges from about 20-40% for highly volatile components to better than 95% for low vapor pressure constituents. The cost-effective curves, if plotted on the same type of figure used in the discussion of surface impoundments and tanks would fall below pretreatment at about 100 pounds per year, a figure well below the capability of any practical land treatment site. No curves have been prepared, however, given the uncertainty in the performance and lack of cost data.

Improved injection (and reduced application rate) cannot, however, achieve high levels of control for the more volatile materials. Loss of in excess of 30-40% of some constituents may be unacceptable. In this case, pretreatment or post-treatment can be used to reach control levels of 90% or better. If pretreatment is feasible, then as in the other cases above, it is considerably cheaper than post-treatment. Some wastes currently being managed at land treatment are not well suited for the pretreatment techniques described by Spivey et al. (1984). For example, some refinery wastes are quite sludge-like, contain a large fraction of solids and, indeed, arise as residues from typical process recovery operations such as distillation.

In such a case, post-treatment using air-inflated structures plus incineration or adsorption would be the choice. If adsorption is used, the recovered wastes can be reapplied. In this mode, performance would be similar to that of the system described earlier where recovered wastes are reinjected in the aerated impoundment over which the cover is installed.

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